DEPARTMENT OF COMMERCE AND LABOR
BUREAU OF STANDARDS
S. W. STRATTON, Director

OPTICAL PYROMETRY

BY

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and
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Bureau of Standards

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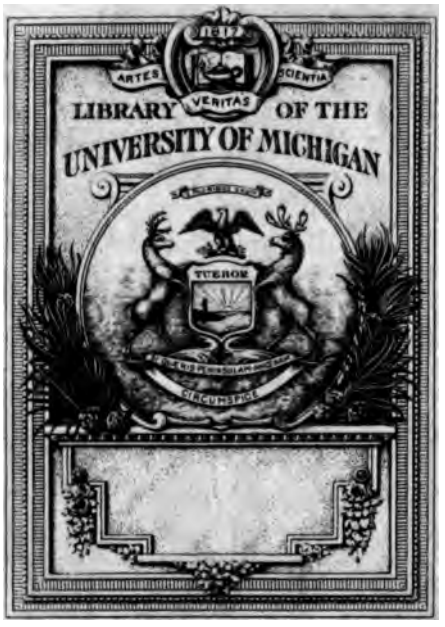
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INTRODUCTION.

It is becoming generally recognized by engineers and technical men in charge of industrial processes carried out at high temperatures that it is usually necessary to measure and control the temperatures of these processes, and many instances might be cited where a change of less than 20° C. in the heat treatment radically alters the resulting product, and often such a small temperature change occurring unnoticed necessitates later the rejection of the completed product.

For a long time the problem of estimating high temperatures was dependent on the trained eye of the workman, but with the high degree of accuracy with which temperatures must be controlled to-day in many specialized lines of work, the requirements are such as can be fulfilled only by the use of a sensitive pyrometer. The two great advantages resulting from the use of the pyrometer, which are at once evident, are:

(1) Once the proper method of working a particular product has been found, this operation can be indefinitely repeated, thus rendering possible the exact duplication of products.

(2) The reproduction of any particular product is no longer locked up in the experience of a few workers, but becomes a matter of permanent record, which may be consulted at any time.

In this connection should be emphasized the advantage arising from the use of the same standard scale of temperature whatever type of pyrometer is employed, for this alone renders possible that important factor in the advance of scientific and technical knowledge—the interchange of experience among men.

There are many instances in practice where it is impossible to make use of any form of pyrometer which must be brought into contact with the substance operated upon, whether it be from the inaccessibility of

the object, its being in motion, or because the contact may be detrimental to the object or pyrometer. For all these cases and also where a rapid examination for the uniformity of temperature over a considerable area is required, some form of pyrometer entirely separated from the substance or furnace and thus acting at a distance is required, that is an optical or radiation pyrometer; and again, for the estimation of very high temperatures, such a pyrometer is the only form of instrument available.

There is an impression current that an optical pyrometer is of necessity a very delicate, mysterious piece of laboratory apparatus, not fitted for shop practice, and not to be trusted except in the hands of an expert, and even then giving results of uncertain reliability; but one of the primary objects of this paper is to show that there are several trustworthy optical pyrometers available, simple in operation, and suited to the most varied and exacting requirements of scientific laboratories and technical works.

In response to numerous inquiries which have been addressed to the Bureau of Standards on the availability and choice of pyrometric methods for particular problems, an experimental investigation of all the leading types of optical pyrometers obtainable has been carried out. This investigation has also been stimulated by the great advances that have been made recently in the development of optical pyrometry, advances resulting in the production of several simple and trustworthy instruments, called into existence on the one hand by the pressing industrial need of them, and rendered possible on the other hand largely by the great progress made during the past ten years in our knowledge of the laws of radiation from incandescent bodies.

These questions will be treated under the following headings:

(1) General discussion of optical pyrometry;

(2) Laws of radiation;

(3) Methods of optical pyrometry;

(4) Description of instruments, including their calibration, range, sources of error, and precision;

(5) Comparison of various types of optical pyrometers;

(6) Special problems in optical pyrometry.

It may be well to state at this point by way of explanation of the method of treatment adopted in this paper, that it has been the aim of the authors to discuss the subject from the point of view of its application primarily to industrial processes, and to answer those questions, that their observations in the shop and consultations with the experts in charge of these processes have shown nearly always arise when the applications of optical pyrometers are considered. Their experience

with these instruments has also strongly impressed them with the wide field of usefulness of these pyrometers in scientific laboratories for many lines of research.

A résumé of the most important work done in recent years on the laws of radiation has been added for the two-fold reason that it is the basis of the entire subject of radiation pyrometry and that this work has not hitherto been available to English readers.[a]

1. General Discussion of Optical Pyrometry.

The temperature of bodies may be estimated from the radiant energy emitted, either in the form of visible light radiation or of the longer infra red waves that are studied by their thermal effects. For the estimation of temperature in this way use is made of the so-called laws of radiation. It would be beyond the scope of this paper to more than briefly outline the researches that have been made in recent years bearing on the laws of radiation. All that will be attempted here will be a statement of these laws, with a brief outline of the experimental evidence on which they are based, and the way in which they have been applied to give an idea of temperatures beyond the range of all ordinary pyrometers that have to be exposed to the temperatures to be measured, e. g., the temperatures of the filament of an incandescent lamp, the electric arc, the electric furnace, and the boiling points of metals.

A number of excellent pyrometers have been introduced into practice that are based on the photometric measurement of the intensity of the light emitted by incandescent bodies.

Most of these pyrometers measure photometrically the intensity of the red radiation. This is done for two reasons, first, because the color of the light from the incandescent source will undergo wide variations as the temperature changes and it will thus be difficult to compare it with the light from some standard source, so that by passing the radiation from both sources through a red glass (or prism) the photometry is reduced to the comparison of two lights of the same color; and secondly, the use of the red radiation enables the measurements to be carried down to lower temperatures, as red light is the first to become visible.

When we consider the enormous increase in the intensity of the light with rise in temperature, this method appears especially well adapted to the measurement of high temperatures. Thus, for example, if the intensity of the red light $\lambda=0.656\mu$, emitted by a body at

[a] Since the beginning of this work an excellent discussion of the laws of radiation by A. L. Day and C. E. Van Orstrand has appeared in the Astrophys. J., **19**, p. 1; 1904.

1000° C. is called 1, at 1500° C. the intensity will be over 130, and at 2000° C. over 2100 times as great. The rapid increase of the photometric intensity of the light in comparison with that of the temperature is also shown by the following table from a paper by Lummer and Kurlbaum,[a] for light emitted by incandescent platinum. The strip of platinum, made in the form of a hollow cylinder, was heated electrically and the intensity of the light emitted from its surface was measured photometrically. The corresponding temperatures were measured by a thermocouple placed inside the platinum cylinder. If I_1 and I_2 are the intensities of the light emitted at the absolute temperatures T_1 and T_2 (not differing many degrees from one another), then if we write

$$\frac{I_1}{I_2}=\left(\frac{T_1}{T_2}\right)^x$$

the values of x at various absolute temperatures (t°C+273°) are as follows:

T° abs.	x
900°	30
1000°	25
1100°	21
1200°	19
1400°	18
1600°	15
1900°	14

From this table[b] it will be seen that at 1000° absolute (727° C.) the intensity of the light increases twenty-five times as rapidly as the temperature; at 1900° absolute (1627° C.) fourteen times as rapidly.

It is this rapid change in intensity of light with change in temperature that makes it possible for the trained eye of the workman to estimate the approximate temperature in the many industrial operations dependent on temperature control.

It would therefore appear that a system of pyrometry based on the intensity of the light emitted by incandescent bodies would be an ideal one, inasmuch as a comparatively rough measurement of the photometric intensity would measure the temperature quite accurately. This, however, is only partly true; it is limited somewhat by the fact that different bodies, although at the same temperature, emit very different amounts of light. Thus the intensity of the radiation from

[a] Lummer and Kurlbaum: Verh. d. Deutsch. Phys. Ges., 11, p. 89; 1900.

[b] Also these data give approximately Tx=25,000. See E. Rasch. Ann. d. Phys., 14, p. 198; 1904.

incandescent iron or carbon at 1000° C., for example, is many times greater than that emitted by magnesia or polished platinum at the same temperature. In other words, the intensity of the light emitted is not a function of the temperature alone, but is dependent on other properties of the body, such as the condition of its surface and its composition. Consequently, if any conclusions were drawn as to the temperatures of these bodies from the light that they emit, it might lead to large errors.

The possibility of erroneous conclusions that might be drawn from such a system of optical pyrometry is still further emphasized in considering the result to which it would lead if applied to the measurement of the temperatures of flames. Here the intensity of the light would vary with the thickness of the flame in the line of sight. If applied to the measurement of the temperature of a colorless Bunsen flame the method would entirely fail.

At first sight the difficulties here enumerated might seem insurmountable, and sufficient to condemn the use of optical pyrometry. Such, however, is fortunately not the case. It therefore becomes necessary to examine more in detail the principles on which optical pyrometry is based, its limitations, advantages, and the necessary precautions that must be observed in overcoming the difficulties enumerated above. For this purpose it will be necessary to briefly review the recent progress that has been made in the study of the radiation laws giving a connection between temperature and intensity of radiation.

Kirchoff[a] in one of the most important contributions to the theory of radiation was led to the important conception of what he termed a "black body," which he defined as one which would absorb all radiations falling on it, and would neither reflect nor transmit any. He further pointed out clearly the important fact that the radiation from such a body is a function of the temperature alone, and is identical with the radiation inside an inclosure all parts of which have the same temperature. The first experimental realization of a black body as a practical laboratory apparatus, was made by Wien and Lummer[b] by heating the walls of a hollow opaque inclosure as uniformly as possible and observing the radiation coming from the inside through a very small opening in the walls of the inclosure.

It is evident at once that such a body will absorb practically all the radiation incident through the small opening, and this whatever the material of the walls, for, unless the walls are totally reflecting, all

[a] Kirchoff: Pog. Ann., **109**, p. 275; 1860. The important contributions of Balfour Stewart in this field must also be considered.

[b] Wien and Lummer: Wied. Ann., **56**, p. 451; 1895.

the radiation will be absorbed, except that portion which might again escape through the opening; the presence of the opening therefore causes a slight departure from ideal black body conditions.

The radiation from a black body being a function of the temperature only, makes it of great importance in the experimental study of the laws of radiation, where a relation is sought between the temperature of the body and the energy radiated, whether the total energy or the energy associated with some particular wave length.

No body is known whose surface radiation is exactly that of a black body. The radiation from carbon and iron approximates fairly near to black body radiation, while the radiation from polished platinum and the white oxides departs very far from it. Black body radiation corresponding to temperatures from that of liquid air or lower up to 1600° C. (or much higher if suitable materials are chosen)[a] are now available in the laboratory. For temperatures up to about 600° C., this is realized by immersing a metallic or other vessel in a constant temperature bath (liquefied gas, vapor, or fused salt) and observing the radiation from the interior through a small opening in the walls. At higher temperatures it is very difficult to heat the walls of the inclosure uniformly, especially with gas flames. Lummer and Kurlbaum[b] have very satisfactorily overcome this difficulty in their electrically heated black body, which is shown in section in fig. 1.

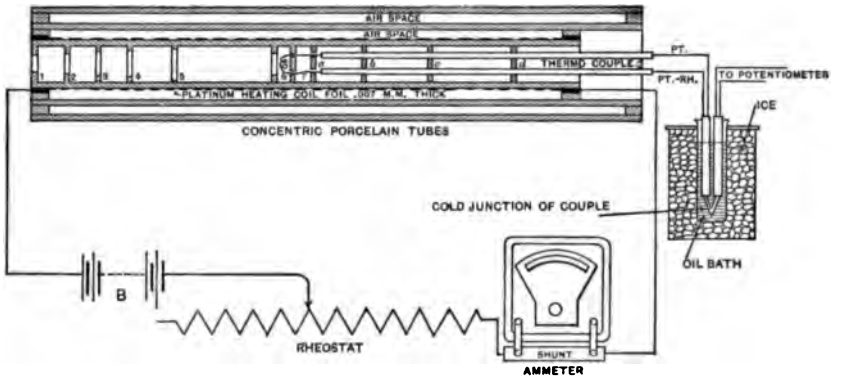

FIG. 1.—Electrically heated black body.

The central porcelain tube is wound over with thin platinum foil through which passes an electric current, which can be adjusted to

[a] Iridium, carbon, or refractory tubes that become conducting at high temperatures.

[b] Lummer and Kurlbaum: Verh. d. Deutsch. Phys. Ges., 17, p. 106–111; 1898. Ann. d. Phys. 117 (4), 5, p. 829–836; 1901.

maintain any desired temperature up to 1600° C. This tube is provided with a number of diaphragms to minimize the disturbing effects of air currents. To protect this inner tube from external influences and to diminish unnecessary heat losses, it is surrounded by several porcelain tubes and air spaces, as shown in the figure. The radiation from the uniformly heated region near the center and which passes out through the end of the tube, is a very close approximation to the ideal black body radiation of Kirchoff. The temperature of this central region is measured by means of a carefully calibrated thermocouple.

As has already been stated, if magnesia, porcelain, platinum, iron, etc., are heated to the same temperature they will emit very different amounts of light. If, however, these bodies[a] are heated inside a black body, they will all emit equal radiation, and on looking into the small opening all details of their contour will be lost, the whole region being of uniform brightness.

An electrically heated black body is used in the calibration of the various radiation pyrometers which will be described later. The question which naturally arises at this point is, what is the use of calibrating an optical pyrometer to measure the temperatures of a black body when in one case the instrument is to be used to measure the temperature of a piece of steel, and in another case the temperature of a piece of porcelain? If the porcelain were actually at a temperature of 1200° C., say, such a calibrated optical pyrometer would give something like 1100° C., because a black body at 1100° C. radiates as much as the porcelain does at 1200° C. On the other hand, for iron at 1200° C. the same optical pyrometer would give about 1140° C., because iron approximates more nearly to a black body. Again, suppose one experimenter has found that in hardening a particular grade of steel a temperature of 700° C. (1290° F.), as measured by a thermocouple, gives the desired product. Then if another experimenter used an optical pyrometer (calibrated against a black body) to measure the temperature of the same grade of steel just before hardening and found it 700° C., (1290° F.) he might get a product very different from that obtained by the first process, and for the reason that the steel would in reality be at a temperature of about 720° C. (at which temperature its radiation is equal to that of a black body at 700° C.).

It is clear that the answer to these questions, or at least a proper understanding of them, is of considerable importance. The most evi-

[a] It is here assumed that the radiation is purely thermal and that no part is due to luminescence, as the laws of radiation are only directly applicable where such is the case.

dent solution is to make the body whose temperature is to be measured as nearly a black body as possible. Then the optical pyrometer will read true temperatures—i. e., the same as a calibrated thermocouple (gas thermometer scale).

For example, if a porcelain tube with closed bottom be immersed into the lead-hardening bath, the radiation coming from the bottom of this tube will be a close approximation to that of a black body, especially if the inside of the tube is blackened with iron or nickel oxide, for example. Again, such a tube, or a metal one, projecting into the gas heating or annealing furnace would solve the problem very satisfactorily. Moreover, in many of the practical cases that arise the conditions fortunately approximate those of a black body. Thus, the temperature of a piece of porcelain is not measured in the open air, but generally inside a furnace whose walls are very often at a temperature not very different from that of the porcelain. The same approximation to black body radiation arises in many cases, e. g., a pot of glass in the furnace, interior of kilns, annealing furnaces, etc. In many other cases, however, the radiation is very different from that of a black body, as for the white-hot gases from the Bessemer converter for which an optical pyrometer would give temperatures several hundred degrees too low. Nevertheless, its indications would always be consistent and would serve as a valuable check on the chemical transformations going on down in the heart of the furnace.

To summarize, the difficulties of and the objections to the use of optical pyrometers, which have been referred to, are then answered in the way already indicated, that in many of the technical operations the radiation is an approximation to black body radiation; in many others it can easily be made so, in which cases the various radiation pyrometers will give true temperatures, and when such ideal conditions can not be approximated, these pyrometers at least give consistent results and will likely be just as useful in most cases as if they recorded true temperatures. Thus in the problem already referred to when the temperature of a hardening bath was measured in one case with a thermocouple and in the other with an optical pyrometer the observer using the latter would soon learn the proper temperature at which to set his optical pyrometer and would then be able to repeat his conditions after that with an accuracy satisfying every requirement.

The term "*black body temperature*" has come into quite extensive use and is of great convenience in the discussion of pyrometric problems. The temperatures indicated by a radiation pyrometer that has been calibrated against a black body are known as black body tempera-

tures. Thus, in the example already given, where a piece of iron and a piece of porcelain were both at 1200° C., the optical pyrometer, which used the red light emitted, gave as the temperature of these bodies 1140° and 1100° C., respectively. This means that iron and porcelain at 1200° C. emit red light of the same intensity as is emitted by a black body at 1140° and 1100° C., respectively. The "black body temperature" of these materials for green light would differ quite appreciably from that for red light. It is evident that if the "black body temperature" of different bodies, e. g., carbon and platinum, are equal, their actual temperatures may differ considerably (80° C. or so, at 1500° C.). This violates the ordinary conception of equal temperatures, which is based on thermal equilibrium between the bodies if brought into contact.

The results of our experiments on radiation from iron and copper oxides, porcelain, fire clay, and platinum are discussed on pages 243–250, under the head of "Departure from black body radiation."

The temperature of any body, therefore, as measured by an optical pyrometer, will in general (luminescence effects excluded) be lower than its true temperature by an amount depending on the departure of its radiation from that of a black body. There is another source of error, however, that may act in the direction of making the pyrometer read too high, namely, due to light reflected by the body whose temperature is being measured coming from surrounding flames and hotter objects. Experiments giving the magnitude of the errors that may arise from this cause and methods of eliminating them are discussed on page 253, under the head of "Diffuse and reflected light."

2. Laws of Radiation.

STEFAN-BOLTZMANN'S LAW.

Naturally the first relation sought between intensity of radiation and temperature was one for the total radiant energy sent out by a body. Numerous attempts to express such a relation were made by Newton, Dulong and Petit, Rosetti, and others. These attempts, however, merely resulted in empirical expressions that held only through narrow ranges of temperature. The first important step was made by Stefan,[a] who, in examining some of the experimental data of Tyndall on the radiation from incandescent platinum wire in the interval 525° C. to 1200° C., was led to the conclusion that the energy

[a] Stefan: Ber. d. K. Akad. d. Wiss., Wien, **79 B**, 2 Abth., p. 391–428; 1879.

radiated was proportional to the fourth power of the absolute temperatures. This relation seemed to be further supported by the best experimental data of other observers, at least to within the limit of accuracy of their observations. Stefan was under the impression that this was a perfectly general relation that held for the radiation of any solid body. Subsequent work has shown that this is not the case, and that it is only true for the energy of total radiation from a black body. This relation received independent confirmation from Boltzmann,[a] who deduced it from thermodynamic reasoning, assuming the existence of the light pressure in the direction of propagation of the wave, as was predicted by Maxwell and by Bartoli, making one further assumption as to the spectral composition of radiation undergoing change of density. The existence of the light pressure has since been determined experimentally by Lebedew[b] and by Nichols and Hull.[c] The remaining assumption made by Boltzmann concerning the spectral composition of the radiation was subsequently proved by Wien. The conditions imposed by Boltzmann, in his discussion on the nature of the radiation, were such as are fulfilled by the radiation from a black body. This relation, which has now come to be generally known as the *Stefan-Boltzmann radiation law*, may then be stated as follows:

The energy radiated by a black body is proportional to the fourth power of the absolute temperature, or

$$E = K(T^4 - T_0^4)$$

where E is the total energy radiated by the body at absolute temperature T to the body at absolute temperature T_0, and K is a constant.

This law has received abundant experimental support throughout the widest range within which temperature measurements can be made from the researches of Lummer, Kurlbaum, Pringsheim, Paschen, and others. Physicists have therefore come to regard this as something more than a purely empirical expression.

An illustration of the experimental evidence in support of this law is given in the following table taken from the experiments of Lummer and Kurlbaum.[d]

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[a] Boltzmann: Wied. Ann., **22**, p. 291; 1884; p. 31; 1884.

[b] Lebedew: Ann. d. Phys., **6**, p. 433; 1901.

[c] E. F. Nichols and G. F. Hull: Phys. Rev., **13**, p. 307; 1901: **17**, pp. 26, 91; 1903.

[d] Lummer and Kurlbaum: Verh. d. Deutsch. Phys. Ges., p. 110; 1898.

Absolute temperature.		$\frac{E}{T^4 - T_0^4}$		
T	T_0	Black body.	Polished platinum.	Iron oxide.
372.8	290.5	108.9	.....	.....
492	290	109.0	4.28	33.1
654	290	108.4	6.56	33.1
795	290	109.9	8.14	36.6
1108	290	109.0	12.18	46.9
1481	290	110.7	16.69	65.3
1761	290	.....	19.64	.....

It will also be seen from this table that while the intensity of the total radiation of iron oxide is four or five times that of polished platinum, it is still considerably less than that emitted by a black body. The total radiation from other than black bodies increases more rapidly than the fourth power of the absolute temperature, so that as the temperature is raised the radiation of all bodies approaches that of the black body.

LAWS OF ENERGY DISTRIBUTION.

Among the first facts to be noticed about the nature of the radiations sent out by bodies were that at low temperatures these radiations consisted of ether waves too long to affect the human eye. As the temperature was raised, shorter and shorter waves were added which could finally be detected by the eye, the first of the visible radiations producing the sensation termed red, then orange, etc., until the violet waves were reached, which were the shortest waves that the eye could detect.

It has long been known that if light from an incandescent source is passed through a prism the waves are spread out into a spectrum with the longer red waves at one end and the shorter violet waves at the other end. When instruments like the thermopile, bolometer, etc., for detecting minute quantities of radiant energy were exposed in the dark region of the spectrum beyond the red, it was found that a very considerable part, indeed the largest part, of the energy of the radiation was present in this region which is termed the *infra-red* part of the spectrum. Similarly by exposing fluorescent substances or photographic plates in the region of the spectrum beyond the violet, it was

found that radiations were also present in the *ultra-violet* part of the spectrum. Müller was among the first to map out the energy corresponding to different wave lengths in the infra-red region of the solar spectrum by exposing a thermopile in different parts of the spectrum. Tyndall, Desains, Curie, Lamansky, and others examined in a similar manner the spectrum of the sun, the electric arc, the lime light, the incandescent platinum lamp, etc. Soon after Langley brought out the bolometer, which was so admirably adapted to the measurement of minute energy of radiations, a great mass of valuable experimental data was obtained bearing on the spectral distribution of the energy of the radiation emitted by various bodies. Among the most important of these contributions must be mentioned the painstaking series of researches of Paschen, who examined the distribution of energy in the emission and absorption spectra of various substances.

Among the experimental facts established by these researches were, that by far the largest portion of the energy in the spectrum was found in the infra-red region, that the position of the wave length having the maximum energy depended on the temperature of the body, and that as the temperature was raised the energy of all the waves emitted increased, but the shorter waves more rapidly than the longer, so that the position (wave length) of maximum energy in the spectrum shifted toward shorter wave lengths. These facts are well illustrated by the curves shown in fig. 2 taken from a paper by Lummer and Pringsheim, in which the ordinates are proportional to the intensity of radiation emitted by a black body, and the abscissæ are wave lengths (in thousandths of a millimeter). Each curve was obtained by keeping the temperature of the radiating source constant, and passing the radiation through a fluorite prism, which has no appreciable selective absorption in the region of the spectrum here studied. The narrow platinum strip of a linear bolometer was then exposed in different parts of the spectrum and the intensity of the radiation, corresponding to different wave lengths, measured by the observed deflections of the galvanometer. These curves show that at temperature 723° abs., the wave length having the maximum energy is 4.08μ, and as the temperature of the radiating source is raised the position of the maximum is steadily shifted toward shorter wave lengths until at 1646° abs. it is at wave length 1.78μ. Such curves as are here shown, where the temperature is constant and the energy is measured corresponding to radiations of different wave lengths emitted by a body, are called *energy curves*, i. e., the relation determined is $J=f(\lambda)$ for $T=$ constant, where $J=$energy corresponding to wave length λ (strictly

the energy comprised in the region of the spectrum between λ and $\lambda+d\lambda$) and T is the absolute temperature of the radiating source

It is also interesting to study the change in the intensity of some particular wave length as the temperature of the radiating source is

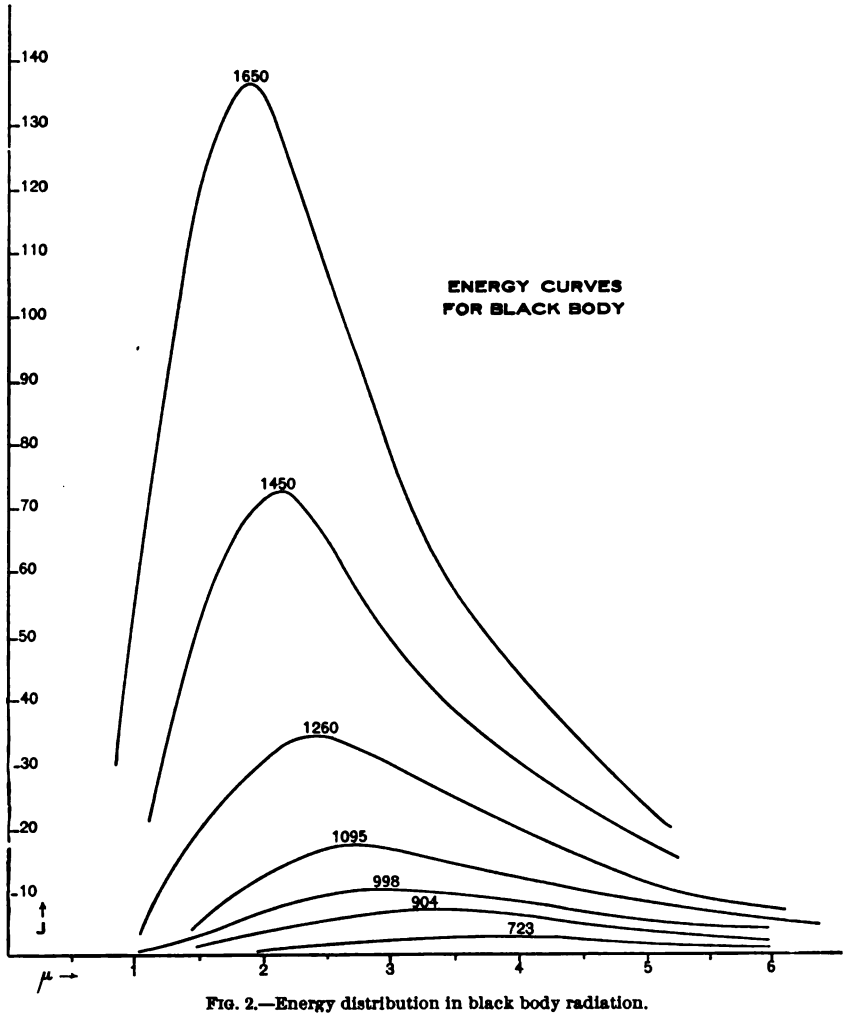

FIG. 2.—Energy distribution in black body radiation.

changed, i. e., to find $J=F(T)$ for $\lambda=$constant. This can be done by exposing the bolometer strip in a fixed part of the spectrum and observing the galvanometer deflections as the temperature is changed. The curves obtained in this way for $J=F(T)$ are called *isochromatic*

curves. Both of these types of spectral radiation curves were first studied in a systematic and thorough manner for a large number of bodies by Paschen, who found that the general form of the radiation curves was the same for all bodies examined by him, i. e., the mathematical relation or form of function giving $J=F(\lambda, T)$ that expressed his experimental results was of the same general type, although the constants in the equations were different for every different body. Under these circumstances it was evidently difficult, if not impossible, to arrive at any general law that would give a relation between J, λ, and T.

WIEN'S LAWS.

This was in brief the experimental state of our knowledge concerning the spectral radiation of bodies, when Wien was led from theoretical considerations to most important generalizations. Starting with the well-grounded assumptions that (1) according to the electromagnetic theory the pressure of the radiation was equal to the energy in unit volume, (2) that the second law of thermodynamics, and (3) that Doppler's principle were applicable, and by postulating the existence of walls (inclosing radiant energy) that were completely black and others that were completely reflecting and diffusing, Wien[a] was led to the conclusion that "when the temperature increases, the wave length of every monochromatic radiation diminishes in such a way that the product of the temperature and the wave length is a constant," i. e.,

$$\lambda T=\lambda_o T_o$$

Hence for the wave length of the maximum energy, λ_m,

$$\lambda_m T=\text{const}=A \tag{I}$$

This is known as the "*displacement law*" and is simply a mathematical statement of the fact that as the temperature of the radiating source is changed the wave length having maximum energy in the spectrum will be changed in such a way that the product of this wave length λ_m and the corresponding absolute temperature of the source T is equal to a constant, i. e., if T increases λ_m shifts toward shorter wave lengths, and if T diminishes the shift is toward longer wave lengths. Wien then combined the above relation with the Stefan-Boltzmann law and was led to the relation that

$$J_{max} T^{-5}=\text{constant}=B \tag{II}$$

[a] Wien: Ber. d. K. Akad. d. Wiss., Berlin, p. 55; 1893. Wied. Ann., **46**, p. 633; 1893; **52**, p. 132, 1894.

in which J_{max} indicates the energy corresponding to the wave length λ_m having maximum energy and T is the absolute temperature of the radiating source (black body).

W. Michelson[a] has criticized the application of the Stefan-Boltzmann law in the way it has been applied by Wien to monochromatic radiation, and takes exception to the use of the term temperature as applied to such radiation existing in the free ether. The above criticisms of Michelson, it seems, take away much of the theoretical support for this law (II). Notwithstanding this, however, both of these generalizations of Wien for the radiation emitted by a black body have received the most convincing experimental verification throughout the widest ranges of measurable temperatures that are at present available to the experimentalist.

For the radiation from other solids that have been examined experimentally it has been found that the "displacement law"

$$\lambda_m T = \text{const} = A_1 \qquad (Ia)$$

still holds true, although the radiation may depart far from that for a black body. In this case, however, the value of the constant is different from that for a black body. Thus for polished platinum Lummer and Pringsheim found $A_1 = 2626$.

For the radiation from other than a black body the law of maximum energy applies only in the modified form

$$J_{max} T^{-\alpha} = \text{const.}$$

Thus for polished platinum Paschen has found $\alpha = 6.42$, while Lummer and Pringsheim find $\alpha = 6.00$.

As an illustration of the experimental evidence in support of these two laws of radiation, the following table has been added, taken from a paper by Lummer and Pringsheim[b] on the radiation from a black body.

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[a] W. Michelson: J. Rus. Phys. Chem. Soc., **34** (5), p. 155; 1902. See Day and Van Orstrand: Astrophys. J., **19**, p. 1; 1904.

[b] Lummer and Pringsheim: Verh. d. Deutsch. Phys. Ges., **I**, p. 218; 1899.

Absolute temperature.	λ_m	E_m	$A=\lambda_m T$	$B=E_m T^{-5}$	$T=\sqrt[5]{E_m/B_{mean}}$	Diff.
°					°	°
1646	1.78	270.6	2928	2246.10^{-17}	1653.5	+7.5
1460.4	2.04	145.0	2979	2184	1460.0	−0.4
1259.0	2.35	68.8	2959	2176	1257.5	−1.5
1094.5	2.71	34.0	2966	2164	1092.3	−2.2
998.5	2.96	21.50	2956	2166	996.5	−2.0
908.5	3.28	13.66	2980	2208	910.1	+1.6
723.0	4.08	4.28	2950	2166	721.5	−1.5
621.2	4.53	2.026	2814	2190	621.3	+0.1
	Means		2940	2188.10^{-17}.		

As will be seen the results of experiment are in most satisfactory agreement with these laws, when one considers the experimental difficulties that are involved in the measurements. In the value for B the temperature enters to the fifth power, so that a small error in the temperature produces a very marked effect on the value of B.

The results of the above table are also shown by the curves in fig. 2, which show very clearly the shift of the maximum toward the visible end of the spectrum with rise in temperature.

Neither the displacement law, $\lambda_m T=\text{const.}$, nor the maximum energy law, $J_m T^{-5}=\text{const.}$, of Wien gives us any information as to the distribution of the energy in the spectrum of a black body at a given temperature. As has already been stated the problem was attacked experimentally by Paschen, who, inasmuch as the black body had not yet been experimentally realized, hoped to arrive at a generalization by measuring the distribution of the energy in the spectra of a number of bodies. As he stated it, "Gesetzmässigkeiten aufzufinden sucht, welche entweder allen Körpern gemeinsamen sind oder umsomehr zu Tage traten, je näher der Körper dem absolut schwarzen kommt."

About this time Wien[a] published the result of a further theoretical investigation on the spectral distribution of energy in the radiation of a black body, in which he was led to the conclusion that the energy corresponding to any wave length was represented by

$$\text{(III)} \qquad J=c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}}$$

[a] Wien: Wied. Ann., 58, p. 662; 1896.

where J is the energy corresponding to wave length λ (region of spectrum λ to $\lambda+d\lambda$), T is the absolute temperature of the radiating black body, e is the base of the natural system of logarithms, and c_1 and c_2 are constants.

In general the proof given by Wien is based on thermodynamic reasoning, but it involves some purely arbitrary assumptions as to the radiations sent out by vibrating gaseous molecules, so that, invaluable as has been the result to which this reasoning has led, it can not be claimed that this spectral distribution law of Wien has any strong theoretical basis.

This formula seemed to satisfy very well the experimental data of Paschen[a] and received independent confirmation by Planck,[b] who deduced Wien's formula in an entirely different way by theoretical reasoning based on the electromagnetic theory of light. Planck, however, in his proof was also compelled to make somewhat arbitrary assumptions (in his definition of the entropy of his electric reasonators) so that his conclusions are open to the same criticism as those of Wien.

The further experiments of Paschen,[c] carried out with black bodies of different forms, seemed to be in most satisfactory agreement with this law. Paschen in summing up the results of these investigations says:

> Wien's law may accordingly be regarded as demonstrated as well as the difficulties of the experiments admit, within the range of wave lengths from 9.2μ to 0.7μ (and in the research carried on in conjunction with Wanner[d] to 0.5μ) and within the range of temperature from 1300° C. to 100° C.

With the theoretical confirmation of this law derived from such entirely different points of view, by Wien and by Planck, and with the strong experimental support afforded by the investigations of Paschen, it seemed at the time that the question of distribution of energy in the spectrum of a black body (the so-called Kirchoff function) was fairly solved.

Subsequent experimental work, however, has shown that Wien's

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[a] Paschen: Wied. Ann., **58**, p. 455; 1896.

[b] Planck: Ber. d. Akad. d. Wiss., Berlin, **I**, p. 440; 1899; pp. 57, 715, 1122; 1897; p. 449; 1898. Ann. d. Phys., **I**, pp. 69, 719; 1900.

[c] Paschen: Ber. d. K. Akad. d. Wiss., Berlin, pp. 405, 959; 1899. Astrophys. J., **10**, p. 40; 1899; **11**, p. 288; 1900.

[d] Paschen u. Wanner: Ber. d. K. Akad. d. Wiss., Berlin, **108**, p. 5, 1899. Wanner: Ann. d. Phys., **2**, p. 141; 1900.

distribution law does not hold for long-wave lengths. Thus, Lummer and Pringsheim[a] found for the so-called constant c_2 the following:

λ	1.21μ	4.56μ	8.3μ	12.3μ	17.9μ
c_2	13510	16510	18500	24800	31700

Beckmann,[b] using the long-wave lengths, 24μ, obtained by multiple reflections from fluorite, after the experiments of Rubens and Nichols,[c] found for c_2 24250 (or 26000, as corrected by Rubens[d]). The experiments of Rubens and Kurlbaum[e] and of Paschen[f] confirm these results.

Rayleigh[g] has also criticised the Wien formula on the ground that the function has a maximum, which leads to the improbable result that the energy corresponding to a definite wave length would not go on increasing with rise in temperature beyond a certain point.

A number of other formulæ were proposed which represented empirically the results of experiments for certain regions of the spectrum and for certain temperature ranges somewhat better than the Wien formula. Among these formulæ may be mentioned those of Thiesen,[h] Lummer and Jahnke,[i] and others.

PLANCK'S LAW.

Planck[j] in a further theoretical consideration of the distribution of energy in the radiation of a black body has modified his assumptions and has been led to the following relation:

$$J = C_1' \lambda^{-5} \frac{1}{e^{\frac{c_2}{\lambda T}} - 1}$$

[a] Lummer: Rap. d. Cong. Int., Paris, **2**; 1900. Lummer and Pringsheim: Verh. d. Deutsch. Phys. Ges., **2**, p. 163; 1900. ZS. f. Instrk., **20**, p. 149; 1900.

[b] Beckmann: Inaug. Dissert., Tübingen, 1898.

[c] Rubens and Nichols: Wied. Ann., **60**, p. 418; 1897; Phys. Rev., **4**, p. 314; **5**, pp. 98, 152; 1897.

[d] Rubens: Wied. Ann., **69**, p. 576; 1899.

[e] Rubens and Kurlbaum: Ber. d. K. Akad. d. Wiss., Berlin, p. 929; 1900. Ann. d. Phys., **4**, p. 649, 1901.

[f] Paschen: Verh. d. Deutsch. Phys. Ges., **2**, p. 202; 1900. Ann. d. Phys. **4**, p. 277; 1901.

[g] Rayleigh: Phil. Mag., **49**, p. 539; 1900.

[h] Thiesen: Verh. d. Deutsch. Phys. Ges., **2**, p. 65; 1900.

[i] Lummer and Jahnke: Ann. d. Phys., **3**, p. 283; 1900.

[j] Planck: Verh. d. Deutsch. Phys. Ges., **2**, p. 202; 1900; Ber. d. k. Akad. d. Wiss., Berlin, p. 544; 1901.

An illustration of the remarkable manner in which this equation satisfies the results of experiments throughout the largest range of measurable temperatures and wave lengths is given by the following table taken from the experiments of Rubens and Kurlbaum.[a] This table shows the results of the measurements of the energy of radiation of wave length 51.2 μ, obtained by multiple reflection (Reststrahlen) from rock salt surfaces, and the comparison of the several radiation formulæ with these measurements.

Reststrahlen from rock salt, $\lambda=51.2\mu$.

Temperature in °C. t	Absolute temperature. T	E obs.	E Wien.	E Thiesen.	E Rayleigh.	E Lumner and Jahnke.	E Planck.
− 273	0	—	−121.5	− 44	− 20	− 27	− 23.8
− 188	85	− 20.6	−107.5	− 40	− 19	− 24.5	− 21.9
− 80	193	− 11.8	− 48.0	− 21.5	− 11.5	− 13.5	− 12.0
+ 20	293	0	0	0	0	0	0
+ 250	523	+ 31.0	+ 63.5	+ 40.5	+ 28.5	+ 31	+ 30.4
+ 500	773	+ 64.5	+ 96	+ 77	+ 62.5	+ 65.5	+ 63.8
+ 750	1023	+ 98.1	+118	+106	+ 97	+ 99	+ 97.2
+1000	1273	+132.0	+132	+132	+132	+132	+132
+1250	1523	+164.5	+141	+154	+167	+165.5	+166
+1500	1773	+196.8	+147.5	+175	+202	+198	+200
+ ∞	∞	—	+194	+ ∞	+ ∞	+ ∞	+ ∞

The experiments with the "Reststrahlen" from fluorite ($\lambda=24.0\mu$ and 31.6μ) are in equally good agreement with the Planck equation. It is interesting to note that for short wave lengths Planck's equation practically reduces to Wien's, and for long wave lengths to Rayleigh's equation. Wien's equation gives $c_2=5\lambda_m T$ and Planck's $c_2=4.965\lambda_m T$. The difference between Wien's and Planck's equations, for such temperatures and wave lengths whose product λT does not exceed 3000, is within 1 per cent. So that if we make use of a wave length $\lambda=0.65\mu$ in an optical pyrometer, the results would be expressed by Wien's equation with every required degree of accuracy for the highest attainable temperatures (4000° C. or more), and even for the longer waves in the infra red, including by far the largest

[a] Rubens and Kurlbaum: Ber. d. k. Akad. d. Wiss., Berlin, p. 929; 1900; Ann. d. Phys., 4, p. 649; 1901.

part of the energy of total radiation, this equation (Wien's) represents the results of experiment with a very fair degree of approximation.

The remarkable agreement of the Planck equation with the results of experiment throughout the extreme ranges in which it has been tested at least justifies the hope that it is something more than a purely empirical relation, which may some day earn the title of a "law" of nature.

III. Methods of Optical Pyrometry.

The subject of Optical Pyrometry might perhaps be more generally classed under the heads of *pyrometry at a distance*, or *radiation pyrometry*, so as to include all methods in which the pyrometer is separated from the body whose temperature is to be measured; but we shall in general use the single expression, Optical Pyrometry, in what follows.

There are numerous methods which suggest themselves as forming a feasible basis for a system of optical pyrometry, and the fact that certain only of the many possible ways of measuring temperature from a distance have been chosen results naturally from a process of elimination either before or after their attempted application; and again, the fact that there is more than one type of optical pyrometer in general use is evidence of the adaptability of special forms to particular needs.

1. COLOR ESTIMATION.

The most widely used method for the estimation of high temperatures is still, unfortunately, by means of the unaided eye, which was naturally the first one to be employed.

The earliest attempt at gauging temperatures of incandescent bodies was made by Pouillet in 1836,[a] who suggested his color scale, giving a name to represent each hundred-degree interval from dull red, 600°–700° C., to dazzling white, 1600°–1700° C., as estimated by the unaided eye. This scale is still quoted as authoritative in text-books and tables of constants to-day, which is a deplorable fact, as the estimation of color change with temperature is largely a personal matter, and, more than that, varies for the same person with the exterior lighting; and although Pouillet's scale was undoubtedly the best to be had in 1836 and for many years after, yet it is at least 100° C. out over almost its whole range, as interpreted by H. M. Howe and others, as is shown by the following table[b] in which the values of Howe and of White and Taylor were obtained quite independently. The column $\triangle_1$ gives

[a] Pouillet: C. R., 3, p. 784; 1836.

[b] Howe: Eng. & Min. J., 69, p. 75; 1900. White and Taylor: ibid., Dec. 23; 1899.

Pouillet's values less White and Taylor's in degrees Fahrenheit, and column $\triangle_2$ the difference between Howe's and White and Taylor's estimations.

White and Taylor.	C.	F.	Pouillet.	C.	F.	$\triangle_1$	Howe.	C.	F.	$\triangle_2$
							Lowest red visible in dark.	470	878	−90 <P.
			Lowest red....	525	977	.....	Lowest red visible in daylight.	475	887	.....
Dark red, blood red, low red.	566	1050	Dark red.....	700	1292	+242	Dull red.....	550 to 625	1022 to 1157	−28 to −18
Dark cherry red.	635	1175	Lowest cherry.	800	1472	+297				
Cherry, full red.	746	1375	Cherry.....	900	1652	+277	Full cherry....	700	1292	−83
Light red, light cherry.	843	1550	Bright cherry.	1000	1832	+282	Light red.....	850	1562	+12
Orange.....	899	1650	Dark orange..	1100	2012	+362	.....	.....	.....	.....
Light orange...	941	1725	Bright orange.	1200	2192	+467	.....	.....	.....	.....
Yellow.....	996	1825	.....	.....	.....	.....	Full yellow....	950 to 1000	1742 to 1832	−83 to + 7
Light yellow...	1079	1975	.....	.....	.....	.....	Light yellow...	1050	1922	−53
White.....	1205	2200	White.....	1300	2372	+172	White.....	1150	2108	−98
			Very bright white.	1400	2552	.....	.....	.....	.....	.....
			Dazzling white	1500 to 1600	2732 to 2912	.....	.....	.....	.....	.....

It is evident that skilled observers may disagree by 50° C. (90° F.) or more in the estimation of relatively low temperatures by color, and that beyond 1200° C. (2200° F.) it is practically impossible to make eye estimations with any certainty whatever.

Cobalt glasses have sometimes been used to aid the eye to exaggerate the changes in hue but this method is not reliable and varies with the observer and glass used. Similarly, matching the hues against pigments or colored yarns, as has been tried, gives hardly better results. A polarizing apparatus utilizing approximately a single hue was devised by Mesuré and Nouel, which will be described later.

II. PHOTOMETRIC METHODS.

Becquerel,[a] in 1862, was probably the first to attempt the measurement of high temperatures by optical means. Studying the irradiation of incandescent bodies, he suggested the possibility of estimating

[a] Becquerel: C. R., 55, p. 821–829; 1862. Ann. de Chem. et de Phys., (3) 68, p. 49–143; 1863.

their temperatures by means of photometric measurements of the intensity of the red radiation, although he did not develop an instrument suitable for that purpose and many of his observations on the brightness of bodies were incorrect and some of his conclusions in contradiction with Kirchoff's law.

The principle suggested by Becquerel gave rise to the first practicable optical pyrometer, and to-day in the various modified forms still furnishes our most trustworthy and convenient method.

In practice a standard of intensity is chosen, and the brightness of the photometric field illuminated by the red light emitted by the body under observation is varied until it is equal in intensity to that of the standard either by use of an iris diaphragm (Le Chatelier), an absorbing wedge (Féry), or by a polarizing device (Wanner), or the standard light may itself be varied according to some known or empirical relation (Holborn-Kurlbaum, Morse).

For monochromatic black-body radiation, and for the wave lengths of the visible spectrum, Wien's law

$$J = C_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}}$$

is directly applicable to this type of pyrometer.

The above formula may be written

$$\log_{10} J = K_1 + K_2 \frac{1}{T},$$

$$\left\{ \begin{array}{l} \text{where } K_1 = \log c_1 - 5 \log \lambda \text{ and} \\ \qquad K_2 = c_2 \frac{\log e}{\lambda} \end{array} \right.$$

which is a linear relation between $\log J$ and $\frac{1}{T}$, so that it requires measurements of the intensity at two known temperatures only to calibrate an instrument.

If the radiation is not black-body radiation, the same formula holds for calibration and use, but with different values of the constants K_1 and K_2.

Assuming Wien's law to hold, instruments calibrated in terms of it may be used to estimate temperatures indefinitely high.

The pyrometers of Holborn-Kurlbaum and of Morse are based upon an empirical relation between the brightness of a filament and the electric current traversing it when the filament is of the same brightness as the incandescent body under observation. Their calibration, therefore, is not so simple as in the preceding case, as none of the radiation laws apply.

III. RATIO OF INTENSITIES OF TWO WAVE LENGTHS.

Crova, in 1878,[a] devised a method based on the relative variation in intensity of two different monochromatic radiations, red and green; but as Violle has shown, the ratio of intensities of $\lambda = .656\ \mu$ (red) and $\lambda = .482\ \mu$ (blue) varies only in the ratio 1 to 4.5 over a temperature interval of 700° C., and again the lower limit of temperature measurement is given by the green (about 1200° C.) rather than by the red, so that Crova can not be said to have made use of a practicable principle, although he actually used his spectrophotometer in industrial works.

IV. UPPER LIMIT OF THE SPECTRUM.

Another method of hardly greater precision than the last but susceptible of being used at much lower temperatures was also suggested by Crova (loc. cit.); namely, using the upper limit of the spectrum of an incandescent body as a measure of its temperature. Hempel[b] has recently tried this method with a special form of spectroscope and using a luminescent screen for observing when the upper spectrum limit is beyond the visible radiations, but compared with other photometric and radiation pyrometers, only crude results can be obtained.

V. MAXIMUM ENERGY IN SPECTRUM.

(*a*) *Displacement of* λ_m, *Wien's Law I.*—Use might also be made of the displacement law,

$$\lambda_m T = \text{const.}$$

for the determination of temperatures, the constant varying from 2930 for a black body to 2620 for polished platinum; some form of bolometer or thermopile could be used in connection with a dispersion apparatus to locate the position of λ_m in the spectrum.

For substances whose radiation is intermediate between that of a black body and polished platinum the temperature determined by this relation will be between the values

$$\frac{2930}{\lambda_m} \quad \text{and} \quad \frac{2620}{\lambda_m}$$

[a] Crova: Journal de Phys., **7**, p. 357; 1878; **9**, p. 196; 1879. Ann. de Chem et de Phys., (5) **19**, p. 472; 1880.

[b] Hempel: Angewandte Chem., **14**, p. 237; 1901.

As an illustration of this range of limiting temperatures, the results of measurements due to Lummer and Pringsheim[a] may be cited:

	λ_m	T_{max}	T_{min}
Arc light	0.7 μ	4200° abs.	3750° abs.
Nernst lamp	1.2	2450	2200
Welsbach mantle	1.2	2450	2200
Incandescent lamp	1.4	2100	1875
Candle	1.5	1960	1750
Argand burner	1.55	1900	1700

The displacement law is among the best established of the radiation laws, both from the theoretical and experimental side, so that this method is of considerable theoretical interest, yet it is not capable of a high degree of precision on account of the difficulty of locating λ_m, due to the flattened form of the energy curve and the effect of atmospheric absorption.

(*b*) *Magnitude of maximum energy, Wien's Law II.*—The application of the maximum energy law

$$T = C\sqrt[5]{J_{max}}$$

requires the same elaborate installation as the preceding method, and no pyrometer has been constructed utilizing either of these two laws.

VI. TOTAL RADIATION.

Another method available for the determination of temperatures is the measurement of the energy of total radiation, visible and invisible, emitted by a body. It is evident in this case that, with a suitable recording device, the temperature of bodies could be determined even before they glow, and indeed theoretically the method might be applied throughout the whole temperature range, in which the sensibility would be least at temperatures near that of the instrument.

Many instruments have been constructed for the measurement of the energy of total radiation, such as the bolometer of Langley, Crooke's radiometer as modified by Rubens and Nichols, the actinometers of Pouillet and Violle, the thermopile, and the radiomicrometer as developed by Boys.

The use of these instruments in general involves elaborate and special installations, and they have found only limited application in

[a] Lummer and Pringsheim: Verh. d. Deutsch. Phys. Ges., 4, p. 36; 1901.

the laboratory for the measurement of temperature. Féry[a] has recently brought out a convenient instrument called a thermoelectric telescope, based on the energy of total radiation, which is measured by the rise in temperature produced at one junction of a very sensitive thermocouple joined to a direct-reading galvanometer.

If the radiation is that emitted by a black body, the calibration of these instruments may be based on the Stefan-Boltzmann law

$$E = K(T^4 - T_0^4)$$

and they may then be used to measure the temperature of black bodies, and by extrapolation temperatures may be estimated far beyond the upper limit attainable with thermocouples. For bodies departing from the black-body conditions the measurements may be expressed either in black-body temperatures or the calibration must be carried out empirically for every different radiating body observed.

VII. INTERFERENCE METHOD.

D. Berthelot,[b] making use of the law of variation of index of refraction of gases with density on the one hand and with temperature on the other, has devised an interferential gas thermometer at constant pressure which is independent of the containing envelope,[c] and although he has obtained results in admirable agreement with the ordinary gas scale his method of measurement requires a very elaborate installation whose description can only be most briefly given here.

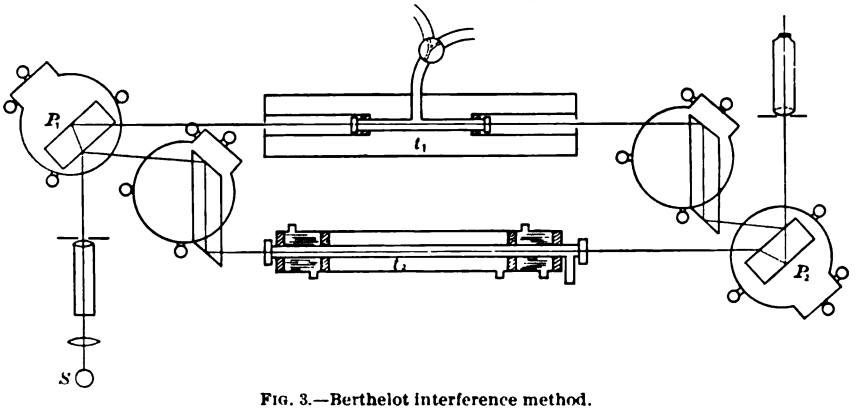

FIG. 3.—Berthelot interference method.

[a] Féry: C. R., **134**, p. 977; 1902.

[b] D. Berthelot: C. R., **120**, p. 831; 1895. Ann. de Chem. et de Phys., (7) **26**, p. 58; 1902.

[c] Provided the envelope does not give off gases or vapors that may influence the results.

Light from a source S is divided into two beams by a thick plate P_1. One beam is passed through a tube t_1 at constant temperature, in which the pressure may be varied; the other passes through the tube t_2, which is heated electrically. The two beams are reunited at the plate P_2 and give a series of interference bands in the eye-piece. The manipulation consists in diminishing the pressure in t_1 as the temperature rises in t_2, so as to always keep the fringes stationary. Then from the relation connecting the temperature of a gas with its pressure, density, and index of refraction, proved to hold throughout a considerable range and assumed to hold for higher temperatures, it can be shown that the temperature of the gas in the hot tube is defined in terms of the *equivalent* lengths of the two tubes and the temperature and pressure of the gas in the cold tube.

This method is evidently an independent system of gas thermometry, and while not in the strict sense of the word a method of optical pyrometry, it may eventually be of service in the extension of the gas scale to higher temperatures than can be obtained by the ordinary forms of gas thermometer, and so serve as an independent check on the radiation laws at these high temperatures.

4. Description of Instruments and Investigation of their Calibration, Range, Sources of Error, and Precision.

Le Chatelier optical pyrometer.[a]

The introduction of a serviceable and simple optical pyrometer was reserved to Le Chatelier in 1892, after he had perfected the thermoelectric pyrometer. Realizing the limitations of the latter for very high temperatures and for inaccessible bodies, he devised his optical pyrometer, which is a modification of Cornu's microphotometer, an instrument for the determination of the brightness of flames. Le Chatelier recognized that he could adjust to equality the two photometric fields from the standard lamp and the incandescent body respectively, either by cutting down the objective aperture, or interposing absorbing screens, or by using a polarizing device. He discarded the last on account of the resulting loss in light and the consequent inability to read relatively low temperatures, and also because the light from incandescent bodies being partially polarized would introduce complications, and he therefore adopted a cat's-eye diaphragm before the objective.

[a] Le Chatelier: C. R., **114**, pp. 214, 470; 1892. J. de Phys., (3) **1**, p. 185; 1892. High Temperature Measurements (Wiley & Sons). This instrument is made by M. Pellin, 21, Rue de l'Odéon, Paris.

Light from the central portion of the flame of a small gasoline lamp L, after passing through the lens L_1, is reflected from the 45° mirror M through a small stop and is brought to a focus in the focal plane of the eyepiece, where it is observed through a red glass. This gives a red comparison field of constant intensity. The lamp L is mounted eccentrically and may be turned so that the image of the flame is exactly bisected by the edge of the mirror M. Light from the incandescent source under observation is focused by the objective and, passing by the edge of the 45° mirror, forms a red field immediately beside and touching the first.

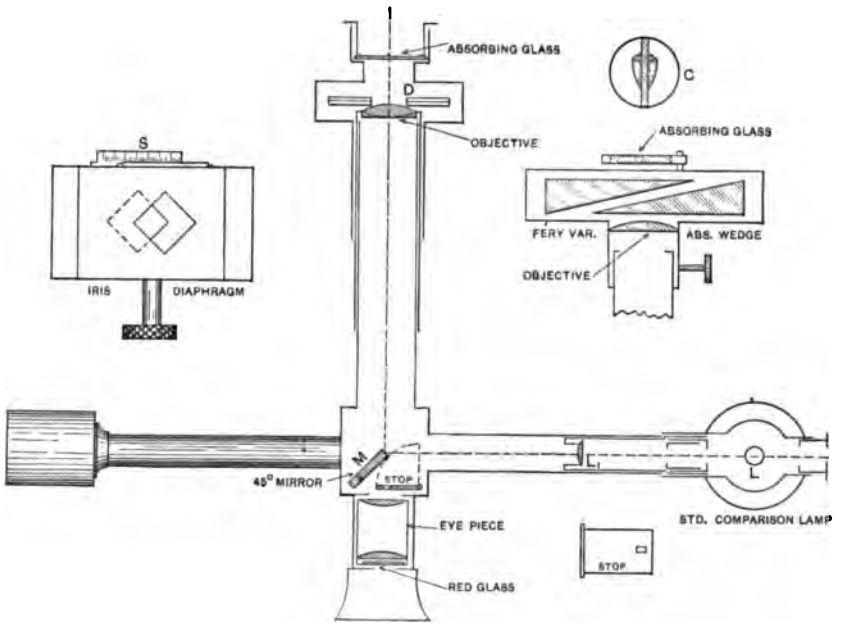

FIG. 4.—Le Chatelier optical pyrometer—section.

A measurement of temperature is made photometrically by bringing the two red fields to the same brightness. This is effected by opening or closing the iris diaphragm D before the objective, thus letting in more or less light from the body whose temperature is sought. For very high temperatures one or more absorbing glasses whose coefficient of absorption is known are placed before the diaphragm opening, and for relatively low temperatures before the comparison lamp. The opening of the iris diaphragm is read on an attached scale, the square of whose readings is a measure of the intensity of the light from the incandescent body.

If K is the coefficient of absorption of the glass before the objective, n' the scale reading of the iris diaphragm when the pyrometer is sighted upon a primary standard of light, as the amyl-acetate lamp—a measurement which may be made once for all—and f' the distance from objective to image, read off the graduated draw tube, and if n and f are the corresponding quantities when viewing the body whose temperature is sought, then the intensity of light from this body in terms of the amyl-acetate flame, taken as unity, is given by the expression

$$J=\left(\frac{n'}{n}\right)^2 \cdot \left(\frac{f}{f'}\right)^2 \cdot \left(\frac{1}{K}\right)^p$$

where p absorbing glasses are used.[a]

When absorbing glasses are placed before the gasoline lamp this formula becomes

$$J=\left(\frac{n'}{n}\right)^2 \cdot \left(\frac{f}{f'}\right)^2 \cdot K^p$$

which applies to temperatures below about 1000° C.

When the pyrometer is always used with the same arrangement of glasses, and at the same distance from the source observed, the expression for J reduces to

$$J=\text{const.} \left(\frac{1}{n}\right)^2$$

Calibration.—It is now necessary to translate the intensity J into temperature. In this operation consists the calibration of the pyrometer. At the time Le Chatelier brought out his instrument in 1892, the laws of monochromatic radiation were not known, so he expressed this calibration by an empirical relation of the form

$$J=10^a \, T^{-\frac{b}{T}}$$

where a and b are constants, whose values depend upon the unit of intensity chosen, and T is the absolute temperature.

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[a] The absorption factor $\left(\frac{1}{K}\right)^p$ is somewhat too large, but owing to the great variation of light in the temperature, this expression is sufficiently accurate for all ordinary ranges of temperature.

As shown on page 210, the calibration of such a pyrometer may be made in terms of Wien's equation (III),

$$\log J = K_1 + K_2 \frac{1}{T}$$

so that if the temperature is known for only two intensities the instrument is completely calibrated for all temperatures, since the relation

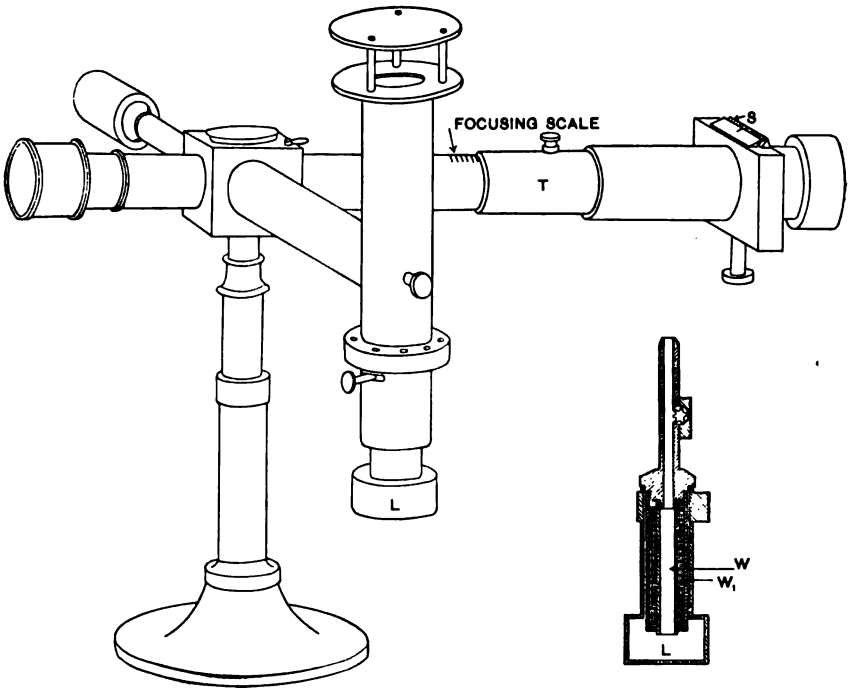

FIG. 5.—Le Chatelier optical pyrometer.

between $\log I$ and $\frac{1}{T}$ is linear, which may be plotted graphically and and then a table may readily be constructed giving T in terms of J or scale readings. Such a table will serve indefinitely for the use of the instrument. Calibration by using Le Chatelier's empirical formula is more tedious and complicated.

The accompanying table shows the results of our calibration of a pyrometer by both methods:

Observed temperature (absolute).	Temperature calculated by Le Chatelier's equation.	(Le Chatelier) $T_{obs}-T_{calc}$	Temperature calculated by Wien's equation.	(Wien) $T_{obs}-T_{calc}$
975°	975°	0°	982°	-- 7°
995	994	+ 1	1001	— 6
1147	1147	0	1150	— 3
1154	1148	+ 6	1150	+ 4
1191	1190	+ 1	1189	+ 2
1211	1214	-- 3	1213	— 2
1278	1276	+ 2	1274	+ 4
1296	1290	+ 6	1287	+ 9
1398	1400	-- 2	1396	+ 2
1459	1464	— 5	1460	— 1
1587	1602	--15	1597	—10

The central portion of the flame of a Hefner standard was used as the unit of intensity. The data satisfy the following equations:[a]

$$\log. J=6.697-9983\frac{1}{T} \qquad \text{(Wien's Eq.)}$$

$$J=10^{7.77}\ T^{-\frac{3660}{T}} \qquad \text{(Le Chatelier's Eq.)}$$

The calibration was carried out by sighting the pyrometer upon the the bottom of a small fire-clay crucible placed at the center of a nickel wound electric furnace 60 cm long and 2 cm opening. Temperatures were measured by two thermocouples with junctions in contact with the crucible.

The effective wave length of the red light transmitted by the glass used before the eye piece was determined as 0.64μ. As shown on page 210, the value of c_2 in the Wien equation is given by

$$K_2=\frac{c_2\log_{10}e}{\lambda}=9983$$

$$\therefore c_2=14700.$$

This would indicate that the radiation from the interior of the electric furnace used in this work is a close approximation to black body radia-

[a] In the computation of the constants of the equations the observations found in the table have not all equal weights.

tion, the constant c_2 for which is about 14500. Covering with iron oxide the radiating fire-clay surface found at the center of the furnace produced no very appreciable increase in the "blackness" of the radiation (not greater than 5° or 10°).

Sources of error.—The sources of error of this instrument may be those due to the Hefner amyl-acetate standard, the oil comparison lamp, the focusing system, the red glass before the eye piece, and the absorption glasses used. The first of these affects only comparative results with different instruments, while the others, if they exist, may be of considerable importance in work with a single instrument. We shall consider them in the order named.

As only the central portion of the amyl-acetate flame is used, variations in height and fluctuations in total intensity, due to various causes, such as moisture and carbonic acid in the atmosphere and changes due to differing samples of acetate, become almost, if not quite, insignificant, so that when using only a small central area of the amyl-acetate flame, it is a very reproducible standard under the most varying conditions of burning. Again the effects of any slight fluctuations in light intensity are further greatly reduced when transformed into temperature changes, as has been shown, page 192. Thus, a variation of one mm in the height of the Hefner flame, which produces a variation of 10 per cent in the total intensity, causes a change of less than 1 per cent in the intensity of light from the central area, which is equivalent to less than 1° C. change in temperature.

When used at intervals, the Hefner serves well enough as an ultimate standard by means of which the indications of all photometer-pyrometers may be reduced to a common basis, yet it is not suited for continuous use as a working standard, for various reasons, an important one being that with continued burning there is considerable charring and an accumulation of a troublesome deposit about the top of the burner.

The comparison lamp used in the pyrometer is a small round-wick lamp (fig. 5) of special construction, burning gasoline preferably, and having an auxiliary feed-wick, which maintains the constancy of burning. This lamp is cleaner than the Hefner, burning for three hours without charring or appreciable accumulation about the burner top. It also burns more steadily, has a more uniform brightness over the flame surface, and remains of constant brightness for considerable variations in the nature of the oil burned.

The other factors which may change the brightness of this flame which we have studied are the effects of time of burning, height of

flame, resetting flame by different observers, kind of oil and depth of oil in lamp.

In order to obtain a perfectly constant source of light with which to compare the oil flame, a 32 c. p. incandescent electric lamp was placed in a fixed position before the objective of the pyrometer and a glass diffusing screen inserted before the objective. The voltage across the lamp terminals was kept rigorously constant, thus giving an arbitrary but invariable standard of illumination.

To control accurately the flame height in the gasoline lamp, a sight was inserted consisting of a horizontal scratch 2 millimeters above the window before the flame and a very fine platinum wire in the same horizontal plane but in a collar behind the flame. With this improvement an observer can set and control the flame height to 0.2 mm The effect of varying the flame height is shown in the following table:

Flame height.	Cats-eye reading.	Δ	Δ in J in per cent.	Δ in T
1 mm high	27.2			
		0.6	4.6	2.5° C.
Normal	26.6			
		0.7	5.2	2.9° C.
1 mm low	25.9			

This shows that for most purposes changes of over 2 mm may occur in the flame height with unimportant changes resulting in the temperature estimation.

The concordance of results obtained by different observers setting the flame and observing is shown below:

Observer.	No. 1.	No. 2.	No. 3.
Cat's-eye reading	26.9	26.6	26.5
	26.5	26.3	

Here the greatest variation corresponds to less than one degree in temperature at 1000° C.

Considering the time effect of burning upon the flame height and intensity due to local heating and change of depth of oil, we find the flame ceases creeping up after ten minutes and will then remain at

constant height to within 0.5 mm until the oil is used up (or in three hours).

The constancy of brightness with time is illustrated by the following set of observations, where the flame height was kept constant:

	Cat's-eye reading.	ΔJ in percentage.	Δ in °C
After 25 minutes' burning	26.03		
		1.7	0°.9
After 45 minutes' burning	26.26		
		7.5	4°.2
After 2 hours' burning	27.03		
		5.0	2°.75
After 2¾ hours' burning	26.68		

Thus there was never a variation corresponding to much greater than 4° C. arising from change of intensity with time, showing that the lamp is fed at nearly a constant rate for all stages of burning.

It might be expected that oils of different grades would give widely differing results, yet such did not prove to be the case.

Different samples of gasoline were used and gasoline mixed with a heavy, pure kerosene having a flash point of 135° C., when the following results were obtained, the numbers being the readings of the cat's-eye scale, readings being taken over a considerable period of time.

Gasoline.			Gasoline + x per cent kerosene.			
Sample 1.	Sample 2.	Sample 3.	2 per cent.	5 per cent.	10 per cent.	25 per cent.
26.3	27.3	26.4	26.1	27.8	26.4	26.7
26.4	27.9	26.1	26.3	28.3		
27.1				27.3		
26.1				26.7		

It appears, then, that with a base of any ordinary gasoline there may be considerable variations in the composition of the oil burned with a practicably negligible change resulting in the intensity of the light emitted by the flame. This is of importance in the practical use of the instrument, as it shows that the scale of the instrument is by no means locked up in a single can of gasoline.

From the above it is clear that variations in brightness of the comparison flame due to all possible causes need not produce errors in temperature measurement of over 5° C., that is, as will be shown, within the limits of making the photometric settings.

Considering now the sources of error due to focusing upon the object whose temperature is sought, it is first to be noticed that there is a minimum distance from the object at which the pyrometer can be focused, this distance being somewhat over a meter, depending, of course, upon the focal length of the objective and length of draw tube. There is also a minimum area which can be sighted upon and give an image of sufficient size to completely cover the desired photometric field. This minimum size of object is about 6 mm on a side when the instrument is at its least distance; for greater distances a larger area must be viewed.

The draw tube can easily be set to 2 mm when focusing, and as the image is over 20 cm from the objective in all cases, the resulting error in intensity due to focusing is not greater than 2 per cent, since

$$I=kf^2$$

$$\text{or } \frac{\delta I}{I}=\frac{2\delta f}{f}=\frac{2\times 0.2}{20}=0.02$$

This corresponds to less than 1° C. in temperature, showing that an error of even 5 mm in focusing the draw tube will hardly produce an appreciable error in temperature estimation.

Often, in use, the distance of the instrument from the objects studied needs to be changed considerably, and in rapid work it is not always convenient to refocus. We find that a change in this distance of a fourth its value—i. e., from 120 cm to 150 cm—will produce only an apparent change in intensity of 9 per cent, or about 5° C. in temperature, at 1000° C., showing that no undue precautions in focusing are needed.

The nonmonochromatism of the red glass before the eyepiece produces no appreciable error in temperature measurement up to 1300° C., although if this glass is not very nearly monochromatic the differences in hue in the two adjacent photometric fields—from the comparison lamp and other source—are very troublesome, and the strain on the eye in matching them is considerable. The three red glasses used were of different make, the best[a] of which let through light between the limits $\lambda=0.60\ \mu$ and $\lambda=0.69\ \mu$,[a] this one proving entirely satisfactory from the photometric point of view. For very high temperatures it would not be safe to assume that Wien's law applies exactly, as there is an appreciable displacement toward the yellow, giving too high

[a] Jena glass No. 2745, obtained from Schott and Genossen.

results for the computed values of the intensity, and so for the temperatures.

There remains to consider the error due to uncertainty in the coefficient of absorption of the absorbing glasses. If an observation (N^1) is taken with and then, at the same temperature, one (N) without an absorption glass, we have

$$K=\left(\frac{N^1}{N}\right)^2$$

so that the accuracy in determining K depends directly upon the precision of setting and reading the cat's-eye opening. The following sets of observations show how closely single observations may be repeated.

	Without absorption glass.				With absorption glass.	
Observer	1	2	3	4*	1	3
Cat's-eye scale, readings.	7.4	7.8	7.6	7.3	25.7	25.8
	7.4	7.9	7.8	7.0	24.0	24.8
	7.2	7.7	7.6	8.0	23.6	26.0
	7.8	7.8	7.7	7.1	24.1	25.8
	7.7	7.7	7.8	8.3	25.4	24.8
	7.8	7.7	7.4	8.0	24.8	24.9
					24.8	25.3
Mean	7.55	7.73	7.65	7.60	24.63	25.34

Observers Nos. 2 and 4 had no experience in the use of the instrument. Observers 1 and 3, over a series of several hundred observations, always differ in the same way as above and by almost exactly the same amount. This constant personal difference is evidently a physiological effect excited by the slight difference in hue of the two halves of the photometric field.

The greatest difference in the means corresponds to 2.5° C. in temperature, and as a set of five observations may easily be taken in two minutes, it is safe to say that the precision of readings is well within 5° C. at 1000° C. The values of K, computed from the results of observers Nos. 1 and 3, differ by 3 per cent, which would introduce a like error into the value of the intensity, but its effect on temperature estimation is equivalent to a difference of less than 2° C. at 1000° C.

In general, it may be said that, with reasonable care, this pyrometer

may be depended on to an order of accuracy of about 1 per cent in the measurement of temperature.

MODIFICATIONS OF THE LE CHATELIER PYROMETER.

For use in technical works and other places where there are strong drafts of air, causing flickering and waving about of the flame of the oil comparison lamp, it seems that the Le Chatelier pyrometer would be improved by the substitution of an electric incandescent lamp of low voltage placed before a uniformly ground diffusing glass screen, which, illuminated by the incandescent lamp, becomes the constant comparison source. The reliability of such a method of producing comparison light of invariable intensity will be discussed when describing the Wanner instrument. We have successfully used this method with the Le Chatelier pyrometer. The electric lamp may be mounted in a vertical arm, which serves at the same time as a handle, and then the instrument becomes as portable as an opera glass.

FÉRY ABSORPTION PYROMETER.[a]

This is identical with Le Chatelier's instrument, except that a pair of absorbing glass wedges replace the iris diaphragm (see fig. 4), and the 45° mirror M, with parallel faces, is silvered over a narrow vertical strip giving a photometric field of form shown at C, when looking at a crucible. The instrument has a fixed angular aperture, so that no correction has to be made for focusing or for varying distance from furnace. The comparison light plays the same rôle as in Le Chatelier's pyrometer, and the range of the instrument may be similarly extended by the use of auxiliary absorbing glasses. Féry has in addition made his instrument movable about a horizontal axis, which is a convenience.

The calibration is equally simple. If x is the thickness of the wedges, read off on a scale, when the light from the comparison lamp and furnace is of the same brightness, then the relation between brightness J and thickness of wedge is

$$J = i\, e^{Kx}$$

where K is the coefficient of absorption of the glass of the wedges for the red light used, and i is a constant.

But by Wien's law, assuming it to apply here,

$$J = A\, e^{-\frac{B}{T}}$$

[a] Féry: J. de Phys., (4) 3, p. 32; 1904. This instrument is made by M. Pellin, 21 Rue de l'Odeon, Paris.

or, combining these two equations,

$$\frac{A}{i}e^{-\frac{B}{T}}=e^{Kx}$$

whence

$$Kx=\frac{A}{i}-\frac{B}{T}=M-\frac{B}{T}\text{ by putting }\frac{A}{i}=M$$

Thus it follows that the thickness of the wedge is inversely proportional to the absolute temperature, so that the calibration may be effected by finding the thickness of wedge for two temperatures only, and plotting a straight line and constructing a table giving $\frac{1}{T}$ and T, respectively, in terms of x.

It is questionable if there is any gain in substituting the wedge for the cat's-eye, in the desire to extend the range over which the instrument may be used, without employing the auxiliary absorbing glasses, for thereby the sensibility is somewhat reduced, and, more important still, the wedge instrument can not be used at such low temperatures as the original Le Chatelier form, nor is there any gain in simplicity of calibration and ease of manipulation. The shape of the photometric field, the use of an aperture of constant angle, and making the instrument movable about a horizontal axis, however, are improvements which may be applied with advantage to the Le Chatelier instrument.

MESURÉ AND NOUEL'S PYROMETRIC TELESCOPE.[a]

In this instrument an attempt is made to control temperatures by taking advantage of the rotation of the plane of polarization of light passing through a quartz plate cut perpendicular to its axis. The angle of rotation is directly proportional to the thickness of the quartz, and approximately inversely proportional to the square of the wave length.

Light from an incandescent object, passing through the slightly ground diffusing glass G, enters a polarizing nicol P, and, traversing the quartz plate Q, strikes the analyzer A, and is viewed through the eye-piece OL. In general, the field of view will be colored, and by turning the analyzer the color observed will change, because the light, all polarized in the same plane emerging from P, is polarized in various planes, depending on the wave length, by the quartz Q, so that the angle between the nicols A and P determines the color that will be seen.

[a] Made by M. Ducretet, 75 Rue Claude-Bernard, Paris.

There is a color to which the eye is particularly sensitive, the transition hue between the red and green, to which the analyzer is turned in taking observations. This sensitive hue is of a lemon-yellow color.

If, then, it is desired to control the constancy of temperature of a heated incandescent body, it is viewed and the instrument set to the sensitive hue, when any change in temperature will cause a change in composition of the transmitted light, and consequently a change in color as viewed through the eye-piece.

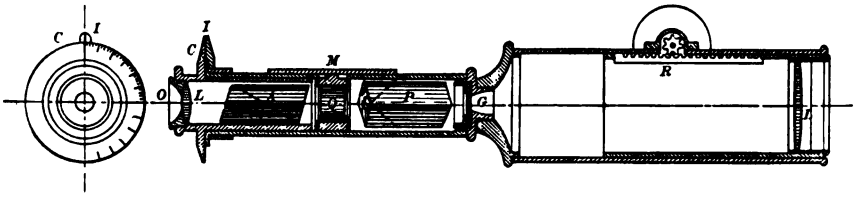

FIG. 6.—Mesuré and Nouel pyrometric telescope.

Besides being used to control heating at a constant temperature, this instrument is sometimes used for estimating the temperatures themselves. For this purpose a circle *C* graduated in degrees is attached to the rotating analyzer and the readings given by the index *I*, when the sensitive hue is reached, are empirically reduced to degrees of temperature. The adjustment of the zero of the scale may be made by removing the quartz at *M*. This pyroscope is rendered more sensitive, especially at low temperatures, by addition of the objective *L*, which is focused by the rack and pinion *R*.

This instrument gives a temperature scale varying not only with different observers but with the same observer at different times, due to the uncertainty in recognizing the sensitive hue. This hue, moreover, is not fixed in color but varies with the temperature, so that the uncertainties of observation easily amount to over 100° C., and even after considerable practice an observer can not be sure of his readings to better than 50° C. at temperatures above 1000° C. This instrument has the advantage over all others, in that it has no auxiliary apparatus whatever, but its lack of sensibility debars it from a place among accurate measuring instruments. It replaces the unaided eye to advantage and its lower limit is about 750° C. It has found its widest use in the ceramic industries.

WANNER PYROMETER.[a]

In 1901 Wanner,[b] making use of the polarizing principle which had been considered but not used by Le Chatelier, brought out a

[a] This instrument is made by Dr. R. Hase, Hanover.

[b] Wanner: Phys. Z. S., **3**, p. 112; 1902. Iron Age, Feb. 18, p. 24; 1904. Stahl und Eisen, **22**, p. 207; 1902.

photometer-pyrometer which is a modification, suited to temperature measurements, of König's spectrophotometer.[a]

The comparison light is a 6-volt incandescent lamp illuminating a glass mat surface. Monochromatic red light is produced by means of a direct vision spectroscope and screen cutting out all but a narrow band in the red, and the photometric comparison is made by adjusting to equal brightness both halves of the photometric field by means of the polarizing arrangement shown in fig. 7.

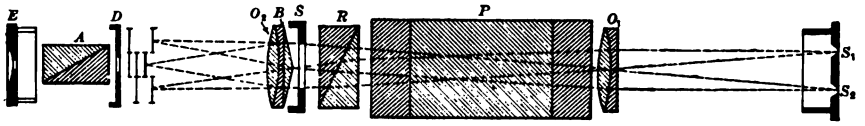

FIG. 7.—Wanner optical pyrometer.

The slit S_1 is illuminated by light from the comparison source reaching S_1 after diffuse reflection from a right-angled prism placed before S_1. Light from the object whose temperature is sought enters the slit S_2. The two beams are rendered parallel by the lens O_1 and each dispersed into a continuous spectrum by the direct-vision prism P. Each of these beams is next separated by a Rochon prism R into two beams polarized in planes at right angles. Considering only the red light there would now be four images formed by the lens O_2 and distributed about the slit D. In order to bring two red images oppositely polarized exactly before this slit, a biprism B is interposed whose angle is such as to effect this for two images only, at the same time increasing the number of images to eight. There is now in the field of view before the nicol analyzer A two contiguous red fields composed of light polarized in planes at right angles, the light of one coming from S_1 and of the other from S_2. All the other images are cut off from the slit D. If the analyzer is at an angle of 45° with the plane of polarization of each beam, and if the illumination of S_1 and S_2 is of the same brightness, the eye will see a single red field of uniform brightness. If one slit receives more light than the other, one-half of the field will brighten, and the two may be brought to equality again by turning the analyzer carrying a graduated scale, which may be calibrated in terms of temperature.

If the analyzer is turned through an angle ϕ to bring the two halves of the field to the same brightness, the relation between the two intensities from S_1 and S_2 is:

$$(a) \qquad \frac{J}{J_o} = \tan^2\phi.$$

[a] König: Wied. Ann., 53, p. 785; 1894.

Since monochromatic light is used, and the comparison beam and that from the object examined undergo the same optical changes, Wien's equation (III) forms the basis of the calibration.

If J_o is the intensity of the light from the standard, and J that from the object whose temperature is sought, Wien's equation gives

$$(b) \qquad \log_{10}\left(\frac{J}{J_o}\right)=\frac{c_2}{\lambda}\log_{10}\epsilon\left(\frac{1}{T_o}-\frac{1}{T}\right).$$

Since the constant c_2 equals 14500 for a black body and $\lambda=0.656\mu$ as the instrument is usually constructed, a knowledge of the apparent black-body temperature of the standard source, together with the reading of the analyzer scale at the normal point when $J=J_o$, is all the data required for the calibration of such an instrument, as any temperature may then be calculated, by means of equations (a) and (b), in terms of the scale readings. This instrument may also, of course, be empirically calibrated against a thermocouple, using a black body to sight upon.

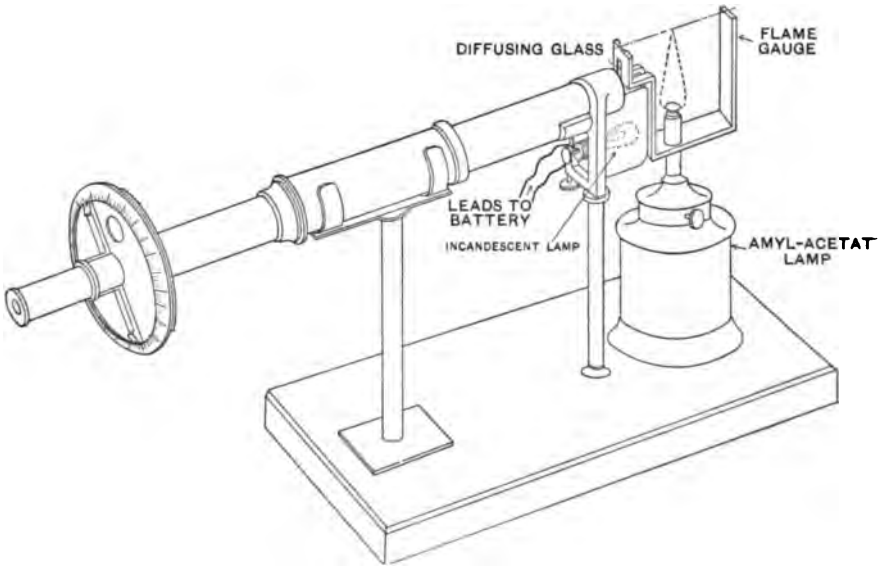

FIG. 8.—Wanner optical pyrometer in position for standardizing.

It is evidently necessary to be able to always reproduce exactly the standard intensity J_o. The brightness of an electric lamp will vary with the current through it, so it is necessary to check frequently the constancy of illumination of the slit S_1 against a standard and constant source of light. An amyl-acetate lamp and a ground-glass diffusing screen can be placed before the slit S_2 thus furnishing the standard

light required. The analyser is then set at the previously determined normal point and the distance of the electric lamp from S_1 and the current through it adjusted until the two fields appear of the same brightness.

Sources of error.—The sensibility of this instrument varies with change in the angle and is so adjusted as to be the greatest between 1000° and 1500° C and is about as follows:

0.1 scale div. =◇= 1° C at 1000° C.
0.1 scale div. =◇= 2° C at 1500° C.
0.1 scale div. =◇= 7° C at 1800° C.

The reproducibility of the brightness of the amyl-acetate flame as viewed through the ground-glass diffusing screen is a measure of the ability of the instrument to repeat its indications. It is very important that this diffusing screen be always placed in exactly the same position relative to the flame and slit S_2, and further, that it be free from dust and finger marks. These requirements can only be satisfactorily met by protecting this screen by a cover-glass and providing an adjustment for setting it exactly in place between the flame and slit.

The constancy of the amyl-acetate flame as used with this pyrometer under ordinary conditions of burning is illustrated by the following set of observations, taken at different times when the current through the electric comparison lamp was kept rigorously constant by means of a milliammeter and rheostat:

Reading of instrument.[a]	Deviations.
39.9	−0.28
39.9	−0.28
40.1	−0.48
39.9	−0.28
39.1	+0.52
39.2	+0.42
39.8	−0.18
39.0	+0.62
Mean 39.62	0.38

[a] 39.6 divs. on the graduated circle ◇1157° C, and at this part of the scale 1 div. ◇7° C.

This shows that the flame can be relied upon to give an intensity of illumination whose constancy expressed in terms of temperature is better than 0.5 per cent. Variations in height of the flame if they do

not exceed 3 mm, together with fluctuations in atmospheric conditions, will not produce errors in temperature estimation exceeding 1 per cent.

The uncertainty of setting the Nicol, due to lack of sensitiveness of the eye to exactly match the two halves of the photometric field, is also about 1 per cent, or somewhat better with practice.

The adjustment of the electric lamp to standard intensity at the point on the scale chosen as normal point, when proper care is taken regarding the diffusing screen, can be made to within 1 per cent expressed in temperature. This source of error does not affect relative results in any one series for one setting to the normal point.

The most serious source of error, except when special precautions are taken, is the variation in brightness of the electric comparison lamp due to variation in the current furnished by the (three cell) storage battery, the percentage change in light being of the order of six times the percentage change in current through the lamp.

The behavior of a battery of 10 ampere-hours capacity furnished with a Wanner instrument is shown by the accompanying plot in which the variations of voltage with time are shown; it will be seen that after making circuit the electromotive force drops by about 2 per cent in two minutes and then falls off slowly, but nearly recovers the original voltage after remaining on open circuit even for a very short time.

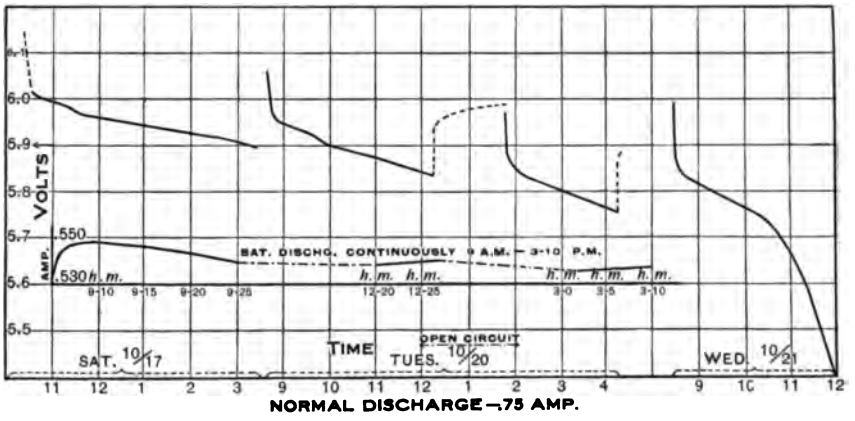

FIG. 9.—Discharge curves of storage battery.

When the battery is in good condition the variation in three hours at normal discharge (0.75 ampere) is about 0.08 volt, and somewhat less for the current (0.55 ampere) taken by the lamp; with the battery in poor condition these changes are much accentuated as shown by the plot.

The following table illustrates the effect of slight variations in current through the lamp on the apparent temperature of the amyl-acetate flame, both for the small 10-ampere-hour battery furnished with the instrument and for a battery of 75-ampere-hours capacity.

Time.	Wanner scale rdg.	Current through lamp.	Per cent change in current through lamp.	Apparent change in temperature observed.
SMALL BATTERY.				
15 min.	31.2	0.5645		
20 "	31.8	0.5640	0.1	1° C.
27 "	32.7	0.5550	1.7	10
37 "	34.6	0.5400	4.3	25
38 "	Disconnected battery 2-minutes.			
40 "	32.5	0.5570	1.5	7
42 "	31.7	0.5610	0.6	3
45 "	32.5	0.5560	1.5	15
47 "	33.1	0.5405	4.1	24
LARGE BATTERY.				
15 min.	37.8	0.5610		
17 "	37.9	0.5590	0.4	2° C.
21 "	39.1	0.5550	1.1	7
26 "	39.3	0.5515	1.7	10
33 "	40.0	0.5455	2.8	17
45 "	40.9	0.5390	3.9	23
52 "	41.1	0.5385	4.0	23
53 "	Disconnected battery 9-minutes.			
63 "	37.2	0.5610	0.0	0
73 "	39.9	0.5460	2.8	17

The above results give abundant evidence of the need of maintaining the current through the lamp quite constant in work of precision. A series of experiments has shown that in the range 1000°–1500° C. one division on the Wanner scale corresponds to about 0.009 amperes, or 1° C. apparent change in temperature is produced by a fluctuation of 0.0012 amperes through the lamp; hence to obtain a precision of 5° C. the current must be kept constant to 1 per cent. The above table and plot show that this is by no means effected by using the battery

without regulating the current, for even with the battery in the best condition the current increases by 2 per cent in the first eight or nine minutes of discharge and then falls off 1 per cent in the next twenty minutes, as shown by the plot. The temperature coefficient of the battery would produce only insignificant changes. The table shows further that even with a large-cell battery, breaking the circuit and then making it again may cause an apparent temperature change of over 20° C. For work of precision, therefore, it is essential to keep the current constant by means of a milliammeter and rheostat.

Range and limitations.—The above description of the Wanner pyrometer has shown the great loss of light due to the optical system employed. This prevents measuring temperatures below about 900° C. (1650° F.) with this instrument. There is no method of sighting this pyrometer exactly upon the spot desired, except by trial, as no image of the object examined is formed in the eyepiece, but this inconvenience is in part compensated by not having to focus with varying distance from the object.

There is another limitation which may in certain cases become a serious source of error. Light from incandescent surfaces is in general partially polarized, and as the Wanner instrument is a polarizing pyrometer, care must be taken to eliminate this source of error when it exists. The magnitude of the error arising from this cause is entirely negligible for all practical purposes for such substances as iron, porcelain, and glass. The results of experiments on the polarization of light from incandescent surfaces are given on page 251.

A review of the sources of error and limitations of the Wanner pyrometer shows that they may exert a relatively large effect on the temperature measurements, and it was therefore thought worth while to emphasize them, but, on the other hand, they may all be kept quite small with reasonable care, and the instrument then becomes one of great precision and convenience.

HOLBORN-KURLBAUM[a] AND MORSE[b] PYROMETERS.

About the same time Holborn and Kurlbaum[c] in Germany and Morse[d] in this country brought out an optical pyrometer using a new photometric method.

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[a] This instrument is made by the Siemens and Halske Aktiengesellschaft, 94 Markgrafenstrasse, Berlin.

[b] This instrument is made by the Morse Thermo-Gr[illegible] Company, Trumansburg, N. Y.

[c] Holborn and Kurlbaum: Ber. d. K. Akad. d. Wi[illegible] Berlin, p. 712; 1901. Ann. d. Phys., 10; p. 225; 1903.

[d] Morse: American Machinist, 1903; U. S. Le[illegible]ers Patent 696878, 696916; 1902.

If a sufficient current is sent through the filament of an electric lamp, the filament glows red at first, and as the current is increased, the filament, getting hotter and hotter, becomes orange, yellow, and white, just as any progressively heated body. If, now, this filament is interposed between the eye and an incandescent object, the current through the lamp may be adjusted until a portion of the filament is of the same color and brightness as the object. When this occurs this part of the filament becomes invisible against the bright background and the current through the lamp then becomes a measure of the temperature of the body under observation.

HOLBORN-KURLBAUM PYROMETER.

A small 4-volt incandescent lamp L with a hairpin filament is mounted in the focal plane of the objective and of the eyepiece of a

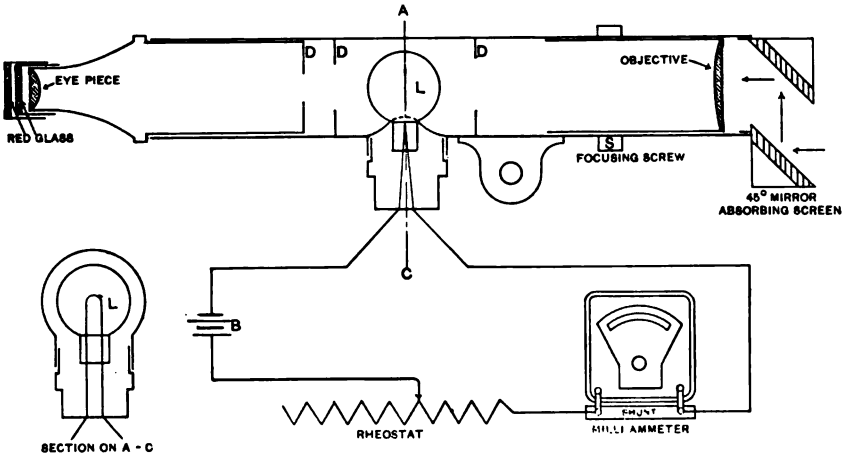

FIG. 10.—Holborn-Kurlbaum optical pyrometer.

telescope provided with suitable stops D, D, D, and a focussing screw, S, for the objective. The lamp circuit is completed through a 2-cell storage battery B, a rheostat, and a milli-ammeter.

The determination of a temperature consists in focussing the instrument upon the incandescent object, thus bringing its image into the plane AC, and adjusting the current by means of the rheostat until the tip of the lamp filament disappears against the bright background, when, from the reading of the milli-ammeter, the temperature can be found from a previous calibration of the lamp giving the relation between the currents through it and the corresponding temperatures of a radiating black body. The calibration will evidently be an independent one for each lamp used.

NOTE.—As a result of recent litigation the Holborn-Kurlbaum Pyrometer has been withdrawn from sale.

As the temperature of the filament increases, the effect of irradiation and too great brightness become blinding, and the photometric comparison is rendered possible at these temperatures by the introduction of one or more monochromatic red glasses before the eyepiece, giving as well all the advantages of photometry of a single color. Below 800° C. the measurements are more easily made without any red glass, as the filament itself is then red and the lowest temperatures are of course reached with the least interposition possible of absorbing media. The lower limit of the instrument is very nearly 600° C. Two red glasses are required for temperatures above 1200° C., and for very high temperatures it is necessary, in order to avoid overheating the lamp filament by the current, to put absorbing glasses or mirrors before the objective, and they also require calibration.

The coefficient of absorption of the absorbing glasses may be calculated by making use of Wien's law, supposing it to hold for the red glass used in the eyepiece. If K is the coefficient of absorption and T_1, T_2 are the apparent black-body temperatures (absolute) given by the pyrometer, sighting first without and then with the absorbing glasses, Wien's equation gives:

$$\log_{10} K=\log_{10}\frac{J_1}{J_2}=\frac{c_2}{\lambda}\log_{10}\varepsilon\left(\frac{1}{T_2}-\frac{1}{T_1}\right)$$

where $c_2=14500$ and λ is the effective wave length for the red glass used. For very high temperatures, although this formula will give a consistent scale when K has been determined, the values obtained are in error by amounts depending upon the lack of monochromatism of the red glass used and upon the consequent varying absorbing power of the absorption glasses.

The eye is particularly sensitive in recognizing equality of brightness of two surfaces, one in front of the other, and this pyrometer therefore provides a very delicate means of judging temperatures. The precision attainable with this pyrometer is illustrated by the following series of observations, which are indicative of the ordinary performance of the instrument:

Temperature from H. & K. pyrometer.	Temperature from thermocouple.	Temperature from H. & K. pyrometer.	Temperature from thermocouple.
1347° C.	1347° C.	632° C.	634° C.
1351	1347	634	633
1343	1343	633	633
1338	1342	633	632
1342	1342		

Different observers do not differ by any appreciable amount in their readings, and at low temperatures the same values are obtained whether a red glass is used or not.

The relation between current and temperature is sufficiently well expressed by a quadratic formula of the form:

$$C=a+bt+ct^2$$

That this formula gives satisfactory results is shown by observations of Holborn and Kurlbaum, for example, with a lamp satisfying the equation.

$$C\,10^3=170.0+0.1600t+0.0001333t^2$$

C amp.	t obs.	t calc.	Δt
0.340	686° C.	679° C.	−7° C.
.375	778	778	0
.402	844	850	+6
.477	1026	1032	+6
.552	1196	1196	0
.631	1354	1354	0
.712	1504	1504	0

The question whether or not the temperatures indicated by the lamp will repeat themselves for continued burning or aging is a vital one for the permanence of a calibration and hence for the practical usefulness of the pyrometer. Holborn and Kurlbaum, as well as ourselves, have made a thorough study of this possible source of error.

Lamps which have not been aged or burned for some time at a temperature considerably above that at which they will ordinarily be used undergo marked changes and are unreliable, but if properly aged they reach a steady condition, as indicated by the following table of results

obtained by Holborn and Kurlbaum on three lamps. The current is given in each case for a temperature of 1,100° C.

Lamp number	1	2	3
After 20 hours' burning at 1900° C	0.608	0.592	0.589
After 5 hours' burning at 1900° C	.613	.592	.592
After 5 hours' burning at 1900° C	.621	.597	.597
After 5 hours' burning at 1900° C	.622	.599	.600
After 20 hours' burning at 1500° C	.622	.599	.601

The plot below shows the results we have obtained by calibrating a lamp, when new, after twenty hours' aging at 1800° C. and again after forty more hours' aging at 1800°. A number of other lamps were calibrated with similar results. It will be seen that if a lamp

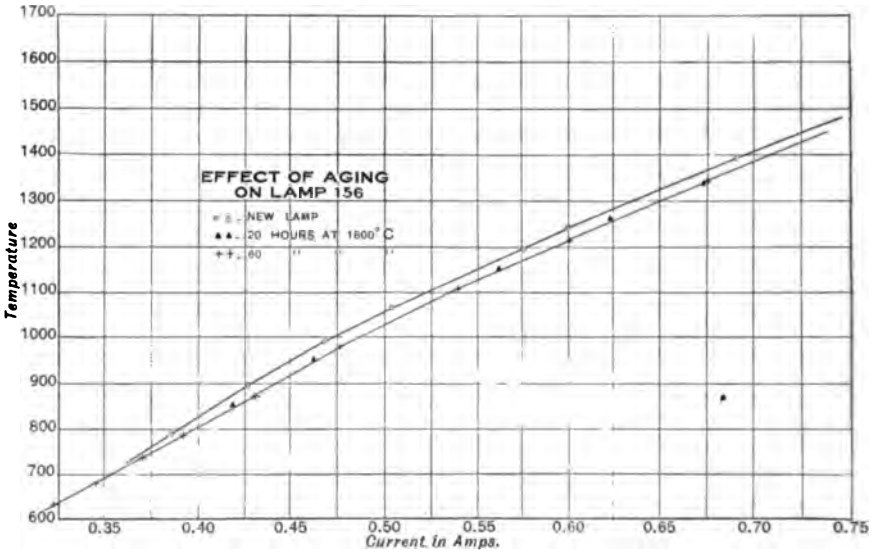

FIG. 11.—Aging of Holborn-Kurlbaum lamp.

is not aged its indications may change by as much as 25° C. with time, but after twenty hours' heating at 1800° it will undergo no further appreciable changes over a period of time corresponding to many months as used intermittently in the shop if not heated above 1500°. This state of permanence is sufficient to satisfy the most rigid requirements of practice.

MORSE PYROMETER.

This instrument, based on exactly the same principle as the Holborn-Kurlbaum, is illustrated in fig. 12. It will only be necessary in describing it to point out the differences in construction.

Instead of a simple hairpin filament, Morse uses a spiral filament S in the lamp L, requiring a battery of twenty to forty volts. In sighting upon an incandescent body it is necessary to choose some particular spot of the spiral and try to make that spot disappear. This is fatiguing, as the spiral covers a large area and is of just sufficiently varying

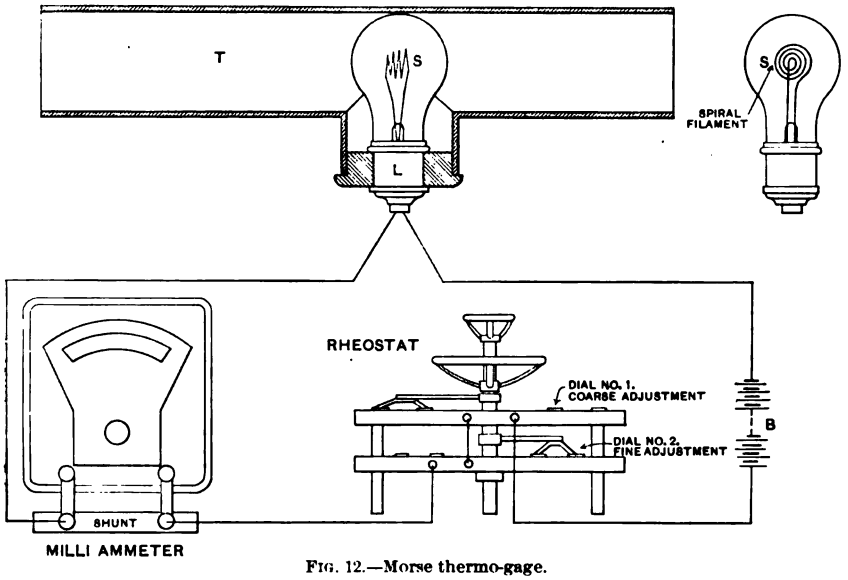

FIG. 12.—Morse thermo-gage.

color to cause the eye to wander. The instrument is not a telescope, possessing no eye-piece or objective, so that the eye has to be trained to recognize the merging of two bright surfaces at different distances. This is readily attained by practice.

The Morse instrument, called a thermo-gage, was designed for use in hardening steel, and throughout the limited temperature range required in this process, in spite of the crudeness of construction above noted, this pyrometer may be read to about 3° C. within this range, and therefore meets, in this respect, all the requirements of technical operations. Above 1200° C., however, it is very difficult and soon becomes impossible to make a satisfactory setting.

In view of the eminently satisfactory results obtained with the low-voltage lamps of Holborn and Kurlbaum, it would seem that there can be little or no gain as to permanence in the higher voltage spiral form

used by Morse. On the contrary, convenience of reading, accuracy of setting, and especially economy of installation and portability of pyrometer and battery, all are in favor of the low-voltage hairpin type.

Our tests of these spiral filament lamps show that when aged at 1200° C. they will remain constant for at least several hundred hours within the range over which they are intended to be used. The Morse instrument would also be greatly improved if provided with a simple focusing device, also with a red glass before the eye for temperatures above 900° C., and an absorbing glass before the lamp for very high temperatures.

It is interesting in this connection to note the behavior of ordinary incandescent lamps as to permanence. The accompanying plot shows the changes in candlepower of an ordinary 16-candlepower incandescent

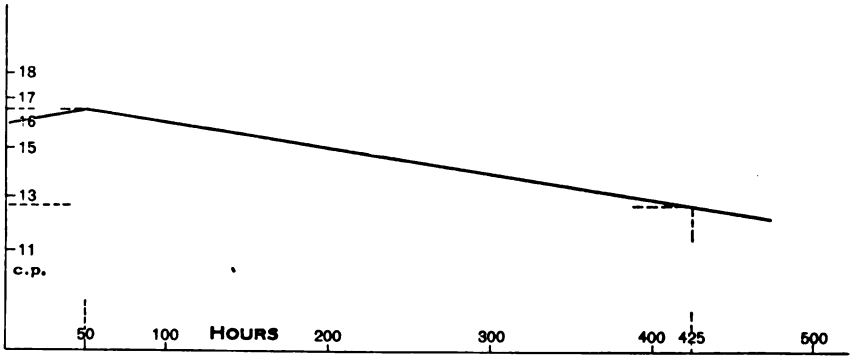

FIG. 13.—Aging of an incandescent lamp.

lamp burning under normal conditions (3.5 watts per candlepower), or with the filament at a temperature of about 1900° C. It is seen that the brightness falls off 20 per cent in 425 hours, and that the relation between candlepower and time is a linear one with a maximum brightness after 50 hours' burning. In terms of temperature the total change in brightness is equivalent to less than 15° C., so that it is evident that an ordinary incandescent lamp run at temperatures less than 1000° C. and used pyrometrically will give a comparison standard which will not change appreciably in temperature over a period of many hundred hours.

FÉRY THERMOELECTRIC TELESCOPE.[a]

This pyrometer is the only form of instrument based on the energy of total radiation which has come into practical use for temperature

[a] Féry: C. R., 134, p. 977; 1902. Ann. d. Chem. et d. Phys. (7), 28, p. 428; 1903. J. de Phys., 8, p. 701; 1904. This instrument is made by M. Pellin, 21 Rue de l'Odeon, Paris.

measurements. As in the case of the photometric pyrometers, the limitations as to the realization of a black body apply here also.

Radiation from an incandescent body is focussed upon a very minute and sensitive thermocouple and raises its temperature. The electromotive force thus generated at the junction actuates a sensitive potential galvanometer in series with the couple, so that we have here a radiation pyrometer which is direct reading by means of a pointer over a scale and could, therefore, readily be made a recording instrument.

The difficulty in construction of such an instrument is in realizing a material for the lens which is transparent for all radiations, so that the pyrometer may be calibrated directly in terms of the Stefan-Boltzmann law. This is effected by the use of a fluorite lens which for temperatures above 900° C. satisfies the conditions of not altering appreciably the radiations transmitted through it; that is to say, the ratio of the radiation absorbed to the radiation transmitted is constant.

At low temperatures a large proportion of the energy exists in the form of long wave lengths, and as fluorite has an absorption band in the infra-red (near 6μ) it will absorb a considerable portion of the radiation, and therefore the Stefan-Boltzmann law can no longer be assumed. With a sufficiently sensitive galvanometer this pyrometer could, however, still be calibrated for low temperatures.

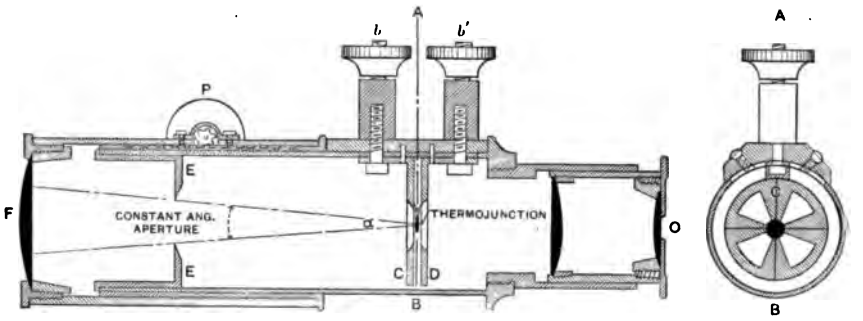

FIG. 14.—Féry thermoelectric telescope.

Fig. 14 illustrates the construction of the instrument where F is the fluorite lens, P a rack and pinion for focussing the radiations upon the thermo-junction of iron-constantan protected from extraneous rays by the screens C, D, shown also in section at AB. The wires of the thermo-couple are of very small dimensions (a few thousandths of a millimeter) and are soldered to a silver disk. The leads are brought out to the insulated binding posts b, b'. The arrangement adopted reduces extraneous thermal currents to a minimum. The circuit is completed through a sensitive galvanometer provided with a scale. A diaphragm

fixed in size and position, EE, gives a cone of rays of constant angular aperture independent of the focusing.

In making a temperature measurement it is necessary to focus the image of the incandescent object upon the thermo-junction by means of the eyepiece O, and care must be taken that this image is of greater size than the junction. This adjustment once made, the pyrometer functions indefinitely while sighted upon the same object, readings of the galvanometer scale giving temperatures directly from the calibration.

The precision attainable with this form of instrument, over the range in which it may be controlled with the thermoelectric pyrometer, is shown from data obtained by Féry, assuming the Stefan-Boltzmann law to hold in the form

$$CE=d=7.66\ T^4\times10^{-12}$$

where E is the total energy of radiation, d the galvanometer deflection, and T the absolute temperature.

d	Temperature from thermocouple.	Temperature from Stefan's law.	Δ in degrees.	Error in percentage.
11.0	844°	860°	+16°	1.85
14.0	914	925	+11	.84
17.7	990	990	0	.0
21.5	1054	1060	+ 6	.60
26.0	1120	1120	± 0	.0
32.2	1192	1190	− 2	.17
38.7	1260	1250	−10	.80
45.7	1328	1320	− 8	.60
52.5	1385	1380	− 5	.36
62.2	1458	1450	− 8	.50

It is evident, furthermore, that if the galvanometer has a uniform scale and the temperature T_1 is known corresponding to any one scale reading R_1, the temperature T_2 for any other reading R_2 may be found from the relation

$$T_2=T_1\sqrt[4]{\frac{R_2}{R_1}}$$

which also shows that errors in the galvanometer readings are divided by 4 when reduced to temperatures. For very high temperatures deflections off the scale of the galvanometer will be obtained. Féry

overcomes this difficulty by substituting a smaller diaphragm before the objective when the radiation is reduced in the ratio of the areas of the apertures. Shunting the galvanometer will also accomplish the same end and this latter method is probably capable of more accuracy.

The laboratory form of apparatus described above is not well suited for use in technical practice, and fluorite is hard to get of sufficient size. The industrial pyrometer is made by substituting for the fluorite lens a much larger one of glass, and for the delicate galvanometer one of the same type and sensibility as is used in thermoelectric work; the resulting instrument is robust and sufficiently sensitive for all practical uses and, as made, has a range from 800° C. to 1600° C., although the upper limit could readily be extended in the manner indicated above.

The indications of the industrial form of this pyrometer will not obey Stefan's law, but the instrument may readily be calibrated by direct comparison, either with a thermo-couple or with a laboratory form of Féry's instrument, and the temperatures engraved on the scale of the pyrometer galvanometer.

Both types of instrument might be constructed so as to reach lower temperatures (650° C.) by means of more sensitive galvanometers, so that this pyrometer could then be used to advantage in steel hardening or other processes requiring relatively low temperatures. Féry[a] has recently brought out a pyrometer in which the energy of radiation is focussed on the thermojunction by means of a concave mirror, thus extending the lower limit to 500° C or thereabouts. The mirror instrument is also the more sensitive.

5. Comparison of Various Types of Optical Pyrometers.

No attempt will here be made to answer the question so often asked, "Which is the best pyrometer?" as it is evident from what precedes that a single answer to this question is impossible. We shall, however, briefly summarize the relative behavior in respect to range, calibration, precision, and permanence of indications of the instruments just described.

As was pointed out, the Mesuré and Nouel pyrometric telescope can not be considered an instrument of precision, although it is serviceable for the approximate control of temperatures above 800° C. (1470° F.), and answers the requirements of many furnace operations sufficiently well. Its great advantage in practical use is that it is encumbered by no accessories whatever.

The Mesuré and Nouel instrument aside, all of the pyrometers dis-

[a] Féry: J. de Phys., 8, p. 701; 1904.

cussed above are capable of an accuracy of 1 per cent in temperature measurement in the ranges for which they are adapted for use. The ease with which this accuracy is attained is not, however, the same in all cases. With the Wanner pyrometer, for instance, this accuracy is not reached unless a milliammeter and rheostat are included in the lamp circuit, and with the Holborn-Kurlbaum and Morse instruments, although this accuracy is readily secured, it must be shown that the lamp used is not undergoing change with continued use in order to maintain this accuracy.

In distinction to the accuracy or absolute reproduction of a given temperature is the precision or relative reliability of results. It is possible to control a given temperature or measure temperature differences much more exactly than reproduce absolutely any temperature. For relative temperature measurements the precision attainable is better than 1 per cent, except possibly for the Féry absorption pyrometer, and may be even as good as 2° at 1500° C. with the Holborn-Kurlbaum instrument.

These different pyrometers as furnished by the makers do not have the same temperature ranges. For reading the lowest attainable temperatures measurable optically, about 600° C. (1100° F.), the instruments available are the Le Chatelier, the Holborn-Kurlbaum, and the Morse and the Féry mirror telescope. The Wanner pyrometer and the Féry thermoelectric telescope have their lower limit at about 900° C. (1650° F.).

Regarding the upper limit, the Morse thermo-gage is difficult to use above 1160° C. (2000° F.) and the industrial form of the Féry thermo-electric telescope as now made reaches 1600° C. (2900° F.), while for all the other instruments the upper limit is indefinitely high or greater than temperatures attainable in industrial practice.

For very high temperatures, above 1500° C., in the region where temperatures can only be determined by extrapolation in terms of some radiation law, the most reliable results will be given by those pyrometers obeying one of these laws the most exactly. Thus instruments calibrated in terms of Wien's law but making use of a red glass which is not monochromatic, as the Le Chatelier, the Féry absorption, and also the Holborn-Kurlbaum pyrometer in the region for which the absorption glasses have to be used, will depart from the true temperature scale more than the Wanner, which, using strictly monochromatic light, will obey Wien's law if the reading circle is correctly graduated and set, although the former instruments will each give an arbitrary temperature scale consistent with itself. The Féry thermo-

electric telescope with fluorite lens calibrated directly in terms of Stefan's law should agree with the photometric pyrometers, as Wien's and Stefan's laws have been found experimentally in accord at the very high temperature of 2000° C.[a]

Regarding the ease of calibration and its control, the Wanner pyrometer and the Féry thermoelectric telescope with fluorite lens are perhaps the simplest, requiring only a single known temperature. Two temperatures are all that are required to calibrate the Le Chatelier and Féry absorption pyrometers, and although several points are necessary for the complete graduation of a Holborn-Kurlbaum or Morse pyrometer, two temperatures are all that is necessary if the instrument is to be used in a small temperature range. The user of an instrument, however, if he has a calibration table does not have to concern himself with this matter unless he has reason to suppose the instrument to be out of order.

The production of a recording optical pyrometer has not been announced as yet by any maker, but it would be a simple matter to render either form of the Féry thermoelectric telescope recording since the indications are given by a pointer over a dial. The other types of pyrometer probably could not by any simple means be made into recording instruments.

Special Problems in Optical Pyrometry.

Departure from black body radiation.—Inasmuch as optical pyrometers are calibrated in terms of the radiation emitted by a black body, the temperature as determined by them will depend, as we have seen, on the nature of the incandescent body observed. It is, therefore, of interest to determine the amount by which such indications differ from true temperatures. With this object in view we have determined the *black body temperatures* of a number of substances at well-known temperatures, as given by the melting points of pure metals and salts.

Radiation from platinum.—Among the substances studied was polished platinum, because it deviates farthest from a black body, and thus gives an idea of the maximum difference to be expected. In these experiments for determinations up to 1500° C. use was made of a Joly meldometer[b] and a Holborn-Kurlbaum optical pyrometer. For experiments at the melting point of platinum a platinum strip about 5 cm long and 4 mm wide was cut narrow at the center, so that the optical pyrometer could be focused on the exact spot at which the

[a] Lummer and Pringsheim: Verh. d. Deutsch. Phys. Ges., (5) 1, p. 3; 1903.
[b] Joly: Proc. Roy. Irish Acad., 2, p. 38; 1891.

strip melted. The electric current through the strip was slowly raised until the strip fused, and the reading of the optical pyrometer at this instant gives the black body temperature corresponding to the melting point of platinum (1780° C.) for the particular color of light used. The results of these experiments are given in the following table, for red ($\lambda=0.651\ \mu$), green ($\lambda=0.550\ \mu$), and blue ($\lambda=0.474\ \mu$) light.

The black body temperature of platinum at its melting point.

Date.	Number lamp used in H-K pyrometer.	Black body temperature for red light. $\lambda=0.651\mu$
1904.		
4/13	156	1545°C.
4/13	156	1543
4/13	156	1550
4/13	156	1530
4/13	156	1520
4/13	156	1526
4/13	156	1541
4/14	156	1528
4/14	156	1547
Mean.	156	1537°C.
4/14	145	1550°C.
4/14	145	1560
Mean.	145	1555°C.
4/14	132	1540°C.
4/14	132	1550
4/14	132	1533
4/14	132	1542
4/14	132	1548
Mean.	132	1543°C.
Final mean		1541°C.
$\Delta=239$°C.[a]		

Date.	Number lamp used in H-K pyrometer.	Black body temperature for green light. $\lambda=0.550\mu$
1904.		
4/18	156	1570°C.
4/18	156	1585
4/18	156	1578
4/18	145	1577°C.
4/18	145	1577
4/18	145	1561
4/18	145	1577
4/18	132	1591°C.
4/18	132	1587
4/18	132	1576
4/18	132	1570
Final mean.....		1577°C.
$\Delta=203$°C.[a]		

Date.	Number lamp used in H-K pyrometer.	Black body temperature for blue light. $\lambda=0.474\mu$
1904.		
4/18	156	1618°C.
4/18	156	1602
4/18	156	1606
4/18	145	1625°C.
4/18	145	1605
4/18	145	1607
4/18	145	1609
4/18	145	1621
Final mean.....		1612°C.
$\Delta=168$°C.[a]		

[a] $\Delta=T-S$, where T=abs. temperature and S=black body temperature.

The radiation from platinum at lower temperatures was studied by fixing the temperature of the platinum strip of the Joly meldometer by means of known melting points in the usual way, by placing a minute

Radiation from platinum.

Red λ = 0.651 μ.				Green λ = 0.550 μ.			Blue λ = 0.474 μ.		
Temperature centigrade.	Date.	No. of lamp used in H-K pyrometer.	Black body temperature.	Date.	No. of lamp used in H-K pyrometer.	Black body temperature.	Date.	No. of lamp used in H-K pyrometer.	Black body temperature.
	1904.			1904.			1904.		
	4/12	145	1381° C.	4/18	156	1402° C.	4/18	156	1434° C.
	"	"	1368	"	"	1402	"	"	1423
1500° C.	"	132	1384	"	145	1410	"	145	1430
	"	"	1370	"	"	1398	"	"	1419
(M. P. of Pd.)	"	156	1368						
	4/14	145	1378		Mean =	1403° C.		Mean =	1426° C.
	"	156	1383			Δ = 97° C.			Δ = 74° C.
	4/11	132	1365						
	"	145	1365						
		Mean =	1374° C. Δ = 126° C.						
1315° C.	4/15	132	1208° C.	4/15	132	1233° C.	4/15	132	1269° C.
	"	156	1210	"	156	1233	"	156	1244
		Mean =	1209° C. Δ = 106° C.		Mean =	1233° C. Δ = 82° C.		Mean =	1256° C. Δ = 59° C.
1215° C.	4/15	132	1122° C.	4/15	132	1135° C.			
	"	156	1117	"	156	1138			
		Mean =	1119° C. Δ = 96° C.		Mean =	1136° C. Δ = 79 C.			
	4/11	156	969° C.	4/14	132	987° C.			
	"	145	967	"	156	985			
	3/23	156	978	"	"	985			
	4/14	132	978	4/15	"	987			
1064° C.	"	145	973	"	"	982			
M. P. of Au.	"	156	980						
	3/23	With Wanner pyrometer.	970		Mean =	985° C. Δ = 79 C.			
	"		971						
	"		974						
			972						
		Mean =	973° C. Δ = 91° C.						
	4/11	145	714° C.						
782 C.	"	132	720						
		Mean =	717° C. Δ = 65° C.						
M. P. of NaCl									
	4/11	145	660° C.						
	"	132	665						
723 C.	"	156	662						
(M.P. of KBr.)		132	670						
		156	670						
		145	671						
		Mean =	666° C. Δ = 57° C.						

specimen of the metal or salt on the strip and slowly increasing the heating current until the specimen was observed to melt, when the length of the strip was determined by the electric contact micrometer screw and the current regulated to maintain this length (and therefore the temperature) constant throughout a series of observations with the optical pyrometer. A second determination of the melting point was always made with the meldometer at the end of every series of observations.

The black body temperatures of polished platinum at 1500° C., 1064° C., 782° C., and 723° C., as fixed by the melting points of Pd,[a] Au, NaCl, and KBr, and at 1315° C. and 1215° C., as fixed by the observed length of the meldometer strip, are given in the table.

The results of all the experiments on platinum are best shown graphically in fig. 15, where for comparison we have added the results obtained by Holborn and Kurlbaum[b] for red light by a somewhat different method.

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[a] The melting point of Pd is uncertain, and 1525° C. is perhaps a better value than the one we have taken (1500° C.). The value for this point as obtained by Holborn and Wien is 1587° C. (Wied. Ann. **56**, 1895) by extrapolation of the thermoelectric relations, but is certainly too high as they determined the gold point 8° too high. Violle found 1500° C. by the specific heat method, which also gave the Pt fusing point as 1780°. Callendar (Phil. Mag., **48**, 1899) with Eumorfopoulos found 1530° C. and 1550° C. by the expansion and resistance of platinum respectively. Taking the Pd point as 1525° C. gives in fig. 11 a value of $\Delta=150°$ C. from our observations so that the T vs. T–S curve would then have no abrupt turn as the platinum point is approached.

[b] Holborn and Kurlbaum: Ann. d. Phys., **10**, p. 225; 1903.

The black body temperature of the melting point of platinum for red light as found by these observers is 1545° C. ($\triangle = 235°$) which is in most satisfactory agreement with the results found by us, which is 1541° ($\triangle = 239°$), obtained by the same method of experiment.

Our results would seem to indicate that the values of $\triangle$ increase somewhat less rapidly with rise in temperature than is indicated by the results of Holborn and Kurlbaum. These differences may arise from several causes. The meldometer strip is probably at a slightly

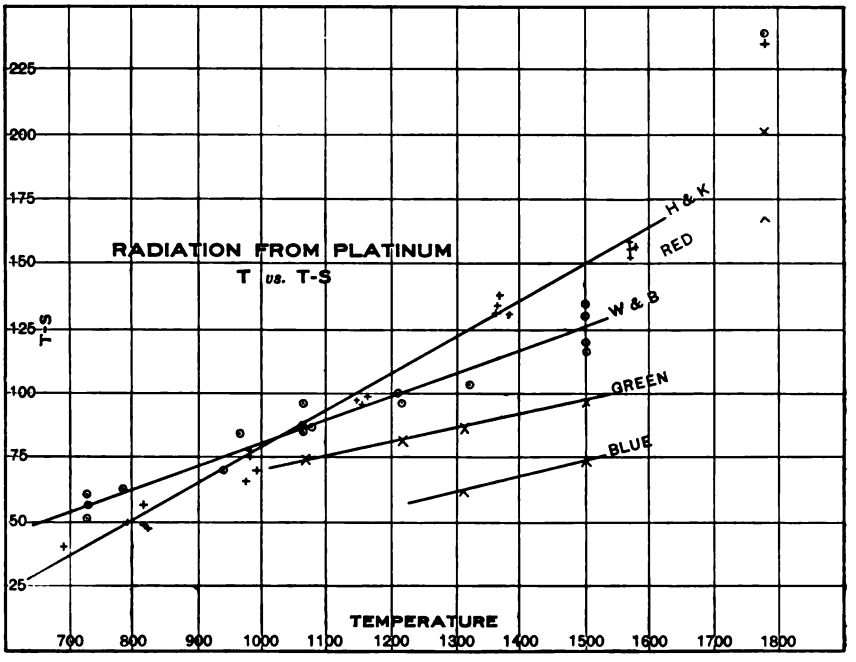

FIG. 15.—Radiation from platinum.

higher temperature than indicated by the melting point calibration and by an amount which is probably greater at high temperatures. This would tend to make the value of $\triangle$ small at high temperatures. In the experiments of Holborn and Kurlbaum the platinum was in the form of a cylinder surrounding a thermocouple. It is thus possible that the couple was at a slightly higher temperature than the outer radiating surface of the platinum, which would tend to increase the values of $\triangle$, especially at high temperatures.

In order to pass through the platinum point ($\triangle = 239°$, red light) a very sudden bend in the curves is necessary (but see note on p. 246). No evidence is yet at hand to explain whether this can in any way be associated with a decreased radiating power of a substance as it approaches a change of state.

It will also be seen, as has been previously shown, that platinum approaches more nearly to black-body radiation for green and blue than for red light.

Radiation from other substances.—Experiments were made on a number of other substances, including clay, copper and iron oxides, and unglazed porcelain to determine the departure of these bodies, at various temperatures, from black-body radiation. Another method of experiment was here necessary, as it is not possible to accurately fix the temperature of oxidizable substances by the meldometer method. The method used will be understood from the following diagrammatic sketch, fig. 16.

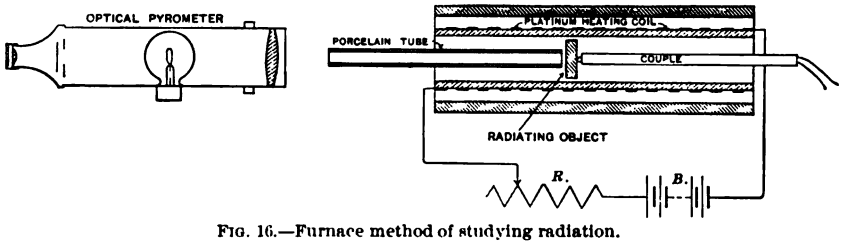

FIG. 16.—Furnace method of studying radiation.

The radiating substance is placed at the center of an electric furnace. The radiations emitted by the substance under these conditions is a very close approximation to black-body radiation, and its temperature as measured by the optical pyrometer will be the true temperature. As a further check on the optical pyrometer a thermocouple in contact with the radiating substance was always read. A porcelain tube, open at both ends and blackened on the interior, was then thrust into the furnace, and the radiation coming out of this cold tube, which is the radiation of that particular substance, was observed with the optical pyrometer. The temperature measured in this way is the equivalent black-body temperature of the substance for the particular color of light used. The tube was then quickly withdrawn and another measurement taken of the true temperature. There was always a slight cooling due to insertion of the tube, which was allowed for by taking the observations in the order indicated above. The results of these experiments giving the departure from black-body radiation are given on page 250.

The experiments at the melting point of copper were carried out in a manner similar to those at the melting point of platinum. A copper strip cut narrow at the center was observed with an optical pyrometer at the instant it was fused by an electric current. The temperature of melting was assumed to be 1065° C., corresponding to the melting point of copper in an oxidizing atmosphere, and the corresponding black-body temperature was given by the optical pyrometer.

In order to compare the *meldometer method* with the *furnace method* we determined the departure of platinum from black-body radiation by both methods. The agreement is even better than we have any right to expect; thus, at 950° C., the furnace method gave 74° C. and the meldometer method (by interpolation) 75° C. as the difference between the true temperature and the black-body temperature of platinum.

The interesting range of iron and steel in which hardening and annealing operations are carried out is from about 600° C. to 950° C., and, as will be seen from the table, the indications of an optical pyrometer in this range, if calibrated in the usual way in terms of black-body radiation, will be low by about 20° at the lower temperature and about 40° at the upper temperature.

The radiation from the fine-grained crucible seemed to be at least as black as that from iron, which would hardly be expected. When a fresh piece of thin Russian iron was inserted into the furnace and measurements were immediately taken with an optical pyrometer, it was observed that the initial readings were some 20° higher at 1000° C. than when the oxidation of the surface was complete, which takes two or three minutes.

Departure from black-body radiation.

Temp. °C.	Platinum.	Iron oxide.	Fine-grain Battersea crucible.	Copper oxide.	Unglazed porcelain.
730°					31°, 35, 25, 30 } 30° C.
750°				22°, 28, 25 } 25° C.	
770°		20°, 26 } 23° C.	11°, 16 } 14° C.		
790°		20°, 21, 22, 26, 23 } 23° C.			
950°	76°, 71, 77, 81, 82, 60, 67 } 74° C.				
980°		43°, 43, 46, 53, 45 } 46° C.			
1050°			50°, 58, 57, 52 } 54° C.		
1065°				37°, 50, 33, 37, 43, 43, 30 } 39° C.	

Polarized light from incandescent surfaces.—Arago was among the first to observe that the light emitted by incandescent surfaces was partially polarized, the amount of polarized light varying widely for different substances, and increasing with the angle at which the surface was viewed, being *nil* in a direction normal to the surface. Prevostaye and Desain, and Magnus, showed that the infra red waves are also polarized in the same plane as the light waves. Arago attributed the polarization to refraction, near the surface, of the light coming from molecules below the surface.

Millikan,[a] who has done the most complete work in this field, has pointed out that this view of Arago fails to explain why the light coming from platinum near grazing emergence is practically completely polarized, for such light must to a large extent be surface light. His experiments indicate that the polarization is a phenomenon of refraction, and that all the light suffers refraction at the surface. Millikan has examined the amount of polarization in the light emitted by a large number of substances. The phenomenon is most marked in platinum, silver, and gold, and is very feeble in the readily oxidizable substances, such as iron, and in such substances as glass and porcelain. It is quite marked for iron in the molten state.

Our experiments have been made mainly with a view to determining the amount by which this phenomenon could influence the indications of optical pyrometers that make use of polarizing devices to adjust to equality the light from the incandescent body observed and from the standard comparison light.

In the experiments on platinum the temperature of the horizontal strip of a Joly meldometer, maintained constant by regulating the electric heating current, was measured with a Wanner optical pyrometer, which employs polarizing devices. To eliminate the effect of the sag of the strip the readings were taken with the pyrometer in four positions at right angles. For each temperature the measurements were made at different angles with the normal to the surface. In rotating the pyrometer the portion of the radiating strip viewed was slightly changed, but an examination of the strip showed that the heating was very uniform, the variations not exceeding 4° over a

[a] Millikan: Phys. Rev., 3, pp. 81, 177; 1895.